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FATIGUE RESISTANCE OF ADHESIVELY BONDED CONNECTIONS

by Harry Nara and Dario Gasparini

prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

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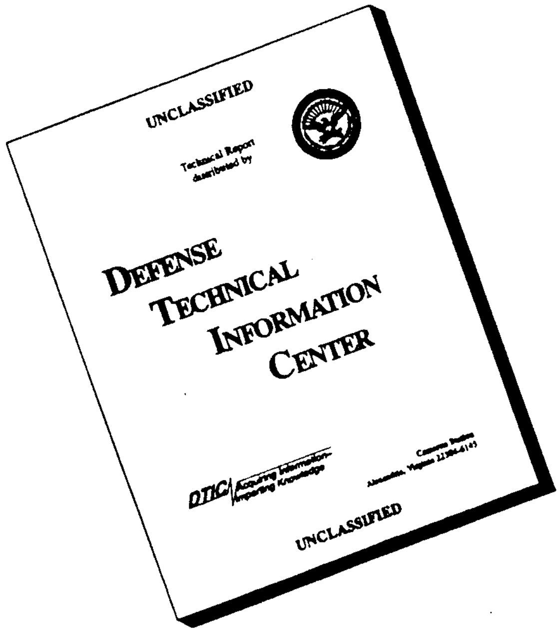

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16. Abstract

It is known that certain welded details adversely affect the fatigue life of bridge members. The utility and feasibility of steel to steel adhesive bonded connections as substitutes for such details is evaluated. Large scale fatigue tests indicated that adhesives can perform structural functions equal to those of welds without decreasing the fatigue life of beams.

Representative adhesive connections on bridges and their performance criteria are broadly defined. Available structural adhesives which satisfy the design criteria are examined. Modified epoxies and acrylics are the structural adhesives most promising for bridge applications. Alternate adhesive constitutive equations and bond strength theories are reviewed. Simple linear elastic adhesive models are not sufficient to explain fully the behavior of bonded joints. Design procedures and experience which may be pertinent for the design of connections on bridges are summarized.

Tests on representative epoxy and acrylic bonded joints, conducted for determining stress-strain properties, tensile, shear, bending and creep-rupture strengths, are reported. Experimental verification of the performance and durability of bonds will be required before an adhesive is used on bridges.

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FATIGUE RESISTANCE OF ADHESIVELY BONDED STRUCTURAL CONNECTIONS

by

Harry Nara and Dario Gasparini

September, 1981

CASE WESTERN RESERVE UNIVERSITY, CLEVELAND, OHIO, 44106

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Steve Marine, the Department technician, assembled the large scale test fixture, made numerous contributions and ran the Amsler fatigue equipment.

Annette Messina ably administered the budget and saw to it that reports were written. The majority of the typing was expertly done by Margery O'Grady.

The authors acknowledge the Ohio Department of Transportation, especially Marty Burke, for suggesting the work, providing information, suggestions and administrative help.

ABSTRACT

It is known that certain welded details adversely affect the fatigue life of bridge members. The utility and feasibility of steel to steel adhesive bonded connections as substitutes for such details is evaluated. Large scale fatigue tests indicated that adhesives can perform structural functions equal to those of welds without decreasing the fatigue life of beams.

Representative adhesive connections on bridges and their performance criteria are broadly defined. Available structural adhesives which satisfy the design criteria are examined. Modified epoxies and acrylics are the structural adhesives most promising for bridge applications. Alternate adhesive constitutive equations and bond strength theories are reviewed. Simple linear elastic adhesive models are not sufficient to explain fully the behavior of bonded joints. Design procedures and experience which may be pertinent for the design of connections on bridges are summarized.

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INTRODUCTION

The primary motivation for studying the feasibility of adhesively bonded connections is the desire to improve the fatigue life of steel bridges. Fisher [71] and others have dramatically demonstrated that fatigue cracks often originate near welded connections of cover plates, near vertical and longitudinal stiffeners and near plate attachments for secondary members. As a consequence of such studies AASHTO Specifications reduce markedly the allowable live load stress range near certain types of connections [86]. As a result, adhesively bonded connections have been proposed as replacements for certain types of welded connections. It is intuitively believed that such adhesively bonded connections will not introduce the flaws, discontinuities, stress concentrations, and changes in metal properties sometimes associated with welds and therefore will not reduce the fatigue life of the base metal of the primary members.

The objectives of the study were then to address the following questions:

a) Do members with adhesively bonded connections have a longer fatigue life than members having analogous (that is, performing equal functions) welded connections?

b) Are adhesively bonded structural connections feasible for steel bridges?

Chapter I of this report describes the work performed in addressing the first question. Broadly, large scale specimens equal to those used by Fisher et al [87], were fabricated with adhesively bonded cover plates, and fatigue tests were conducted.

The approach used to address the second question was as follows:

a) Define, as far as possible, the proposed uses and performance criteria for adhesives on bridges,

b) Classify broad categories of adhesives and bonding procedures,

c) Study mathematical models of adhesive materials, assess available data on engineering properties of adhesives and evaluate the methods used to obtain the properties,

d) Document current experience with adhesives in similar applications,

e) Define currently used engineering design procedures for bonded connections.

The investigation identified issues which must be resolved before adhesives can be used on bridges. Chapters I through VI describe the above studies and report on the experimental results completed thus far.

Broadly, the following conclusions have been reached by the work completed:

1) Beams having adhesively bonded connections can, indeed, have a fatigue life far greater than beams with analogous, welded connections.

2) There is a paucity of data on the engineering properties of adhesives.

3) Some currently used engineering tests are primarily for comparison between adhesives and yield relatively little generally applicable information.

4) The long term durability of adhesively bonded connections in the bridge environment is an unresolved issue.

5) General design approaches for adhesive bonded structural connections remain to be developed.

CHAPTER I

FATIGUE LIFE OF BEAMS WITH ADHESIVELY BONDED COVER PLATES

This chapter describes fatigue tests which were performed to show that adhesively bonded connections, as substitutes for certain welded details, can improve the fatigue performance of beams.

The following criteria defined the type of fatigue specimen used.

1) The specimen should have a bond which substitutes for a welded, AASHTO Category E [86] detail. Category E has the smallest allowable stress range for design conditions having over 2×10^6 cycles of loading.

2) The nominal stress condition of the bond should be easily computable and analogous structural functions should be performed by both the welded and bonded details.

3) Data on standard rolled shapes with and without welded details should be available.

It became apparent that the extensive research conducted by Fisher et al [81] on the effects of weldments on the fatigue life of beams constituted a natural and useful data base. Therefore the specimen which was selected was the "CB" type as reported in NCHRP Report 102 and shown in Fig.1.1. The only difference was that the cover plates were bonded rather than welded onto the beam. Thus a direct comparison of the fatigue lives of the bonded specimens with those reported for plain and welded specimens was meaningful.

The adhesives chosen for bonding were Dexter-Hysol EA934 epoxy adhesive and Lord Corp. Versilok 201 modified acrylic adhesive. Descriptions of these

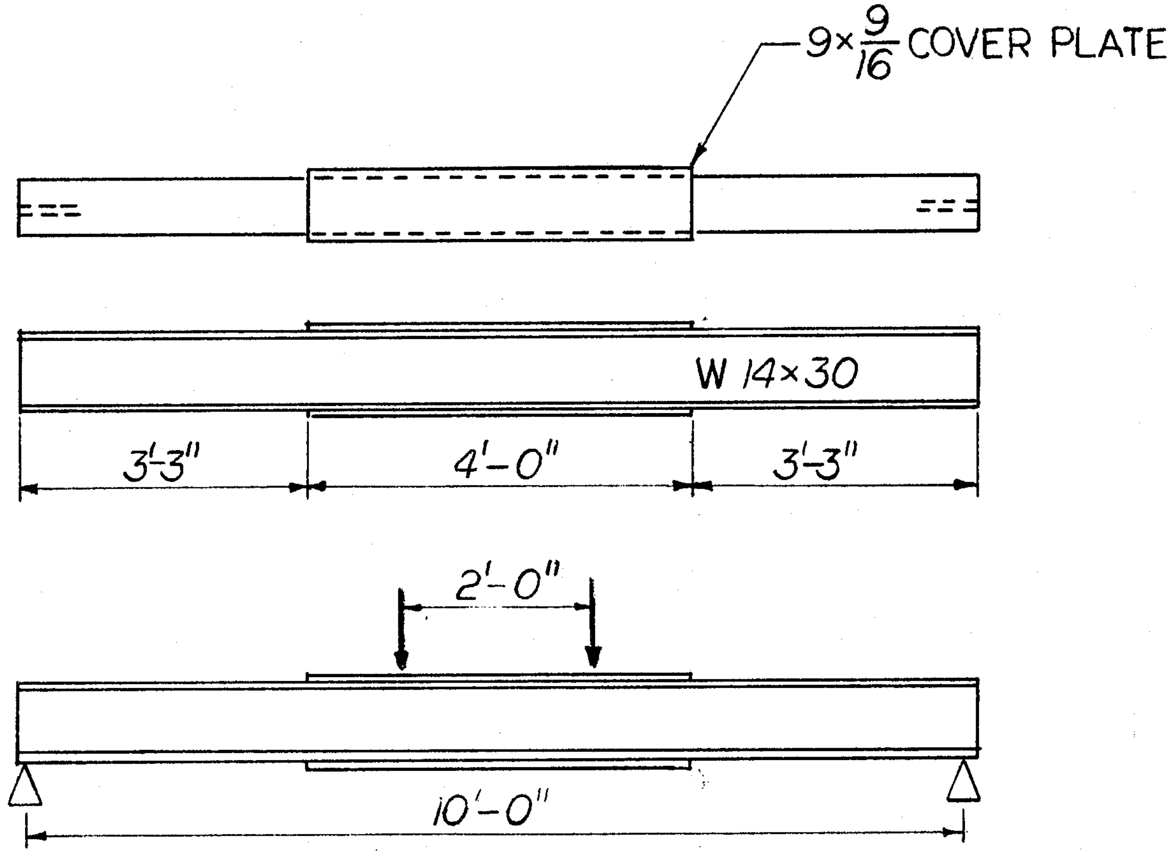


FIG. 1.1 LARGE SCALE FATIGUE SPECIMEN
(FROM NCHRP REPORT 102)

adhesives as well as the rationale for their use are given in Chapter V . It should not be inferred that the Dexter-Hysol EA934 is an optimum epoxy formulation for steel to steel structural bonding; it is simply a representative epoxy product. It is believed that the Lord Corp. Versilok 201 is a state-of-the-art modified acrylic adhesive.

The surface preparation and bonding procedures were as follows: The beam flanges were sandblasted and the surface wiped with the solvent Methyl Ethyl Ketone (MEK). The bonding surfaces on the cover plates were ground (at a commercial "Blanchard grinding" firm), sandblasted and wiped with the solvent MEK. The bondline thickness was controlled by placing 0.010" diameter wire on the bonded surfaces. Since the surfaces of rolled beams are not perfectly flat the adhesive thickness cannot be expected to be uniform throughout. An excess amount of adhesive must be used and squeezed out by hand pressure, forming adhesive "spew fillets" all around. From a practical standpoint, spacing wires must be placed on high spots so that the adhesive is not totally squeezed out from such areas leading to metal to metal contact. (See Figs. 1.2 - 1.6)

Curing of adhesive bonds was at room temperature and slight pressure from clamps was used to prevent slipping between adherends. Although such curing conditions are not optimum for the adhesives, they are feasible for field applications.

The fixture and apparatus used for testing is shown in Fig. 1.7. The primary device used was an Amsler "Pulsator" with one hydraulic jack having a capacity of 110 kips (dynamic) and operating at 260 cpm. The loading arrangement, shown in Fig. 1.1, was the same as that used by Fisher et al [87].

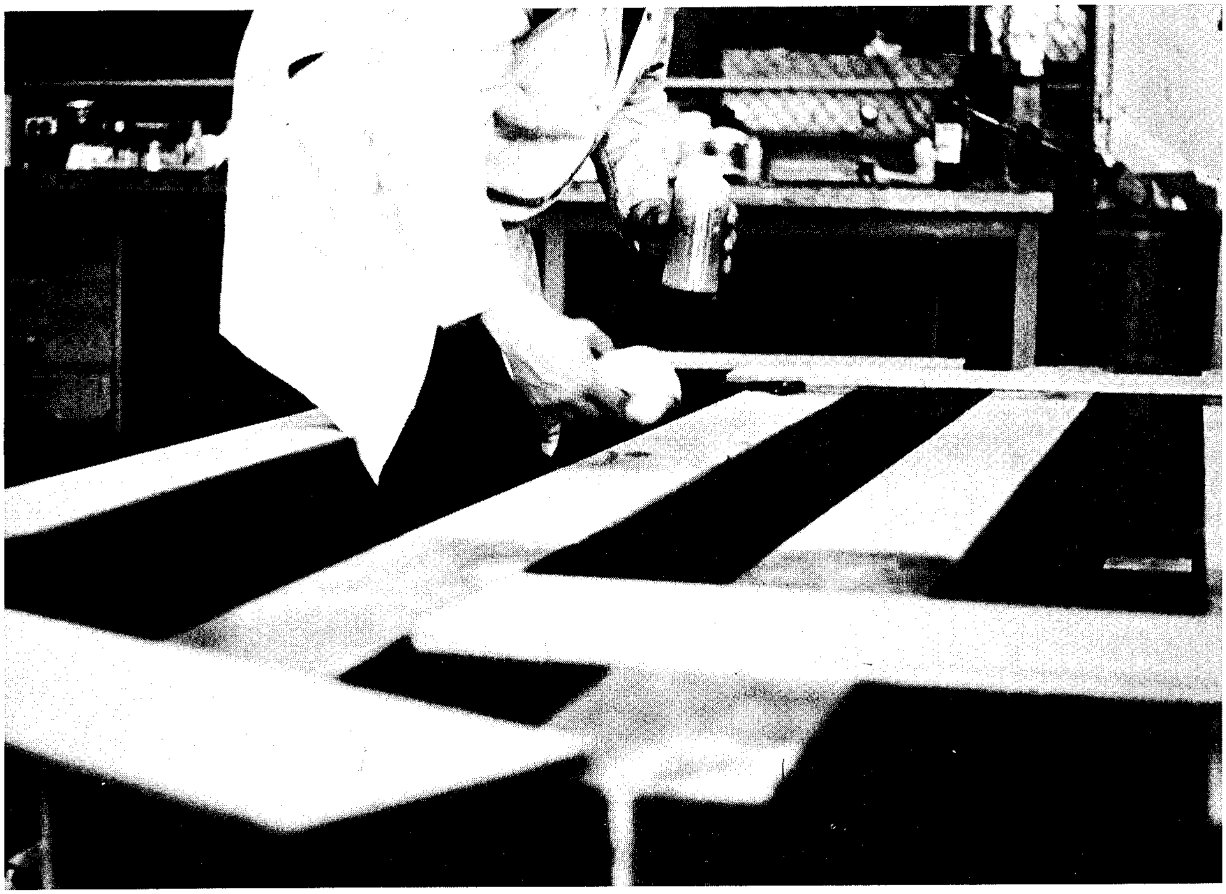


Fig. 1.2

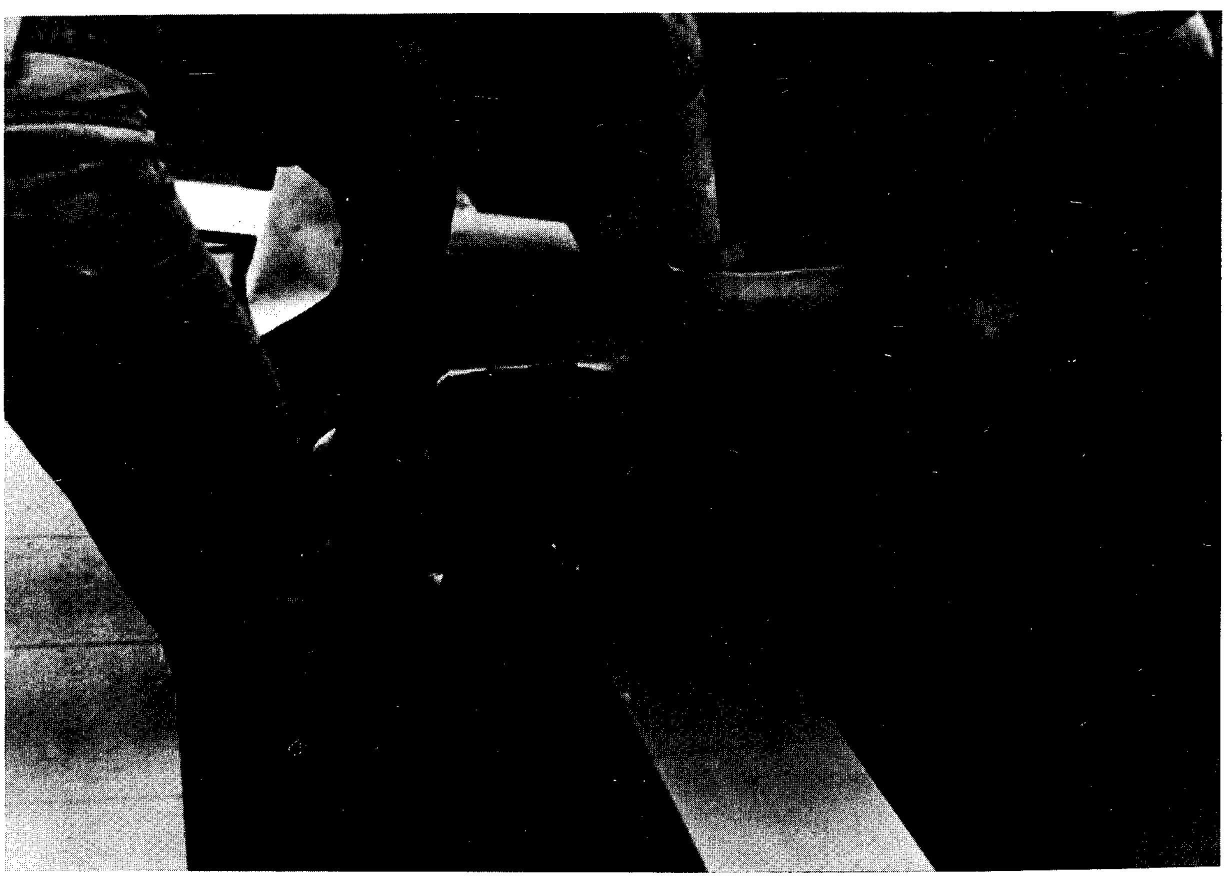


Fig. 1.3

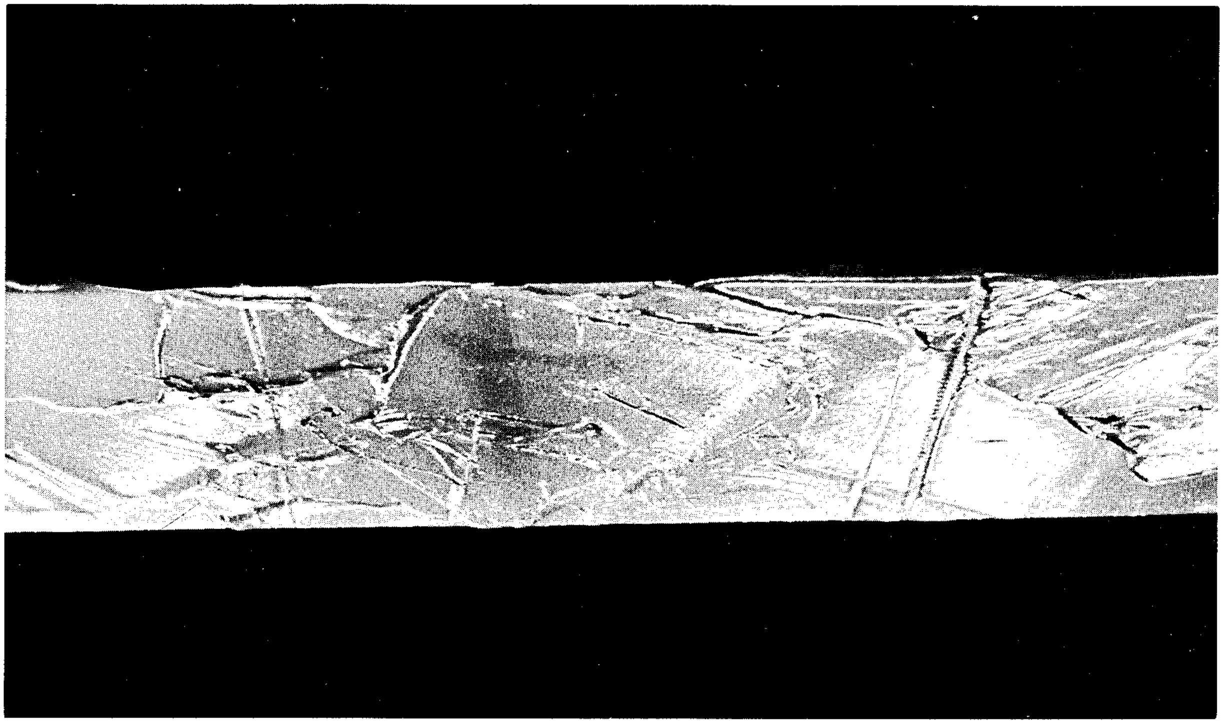


Fig. 1.4

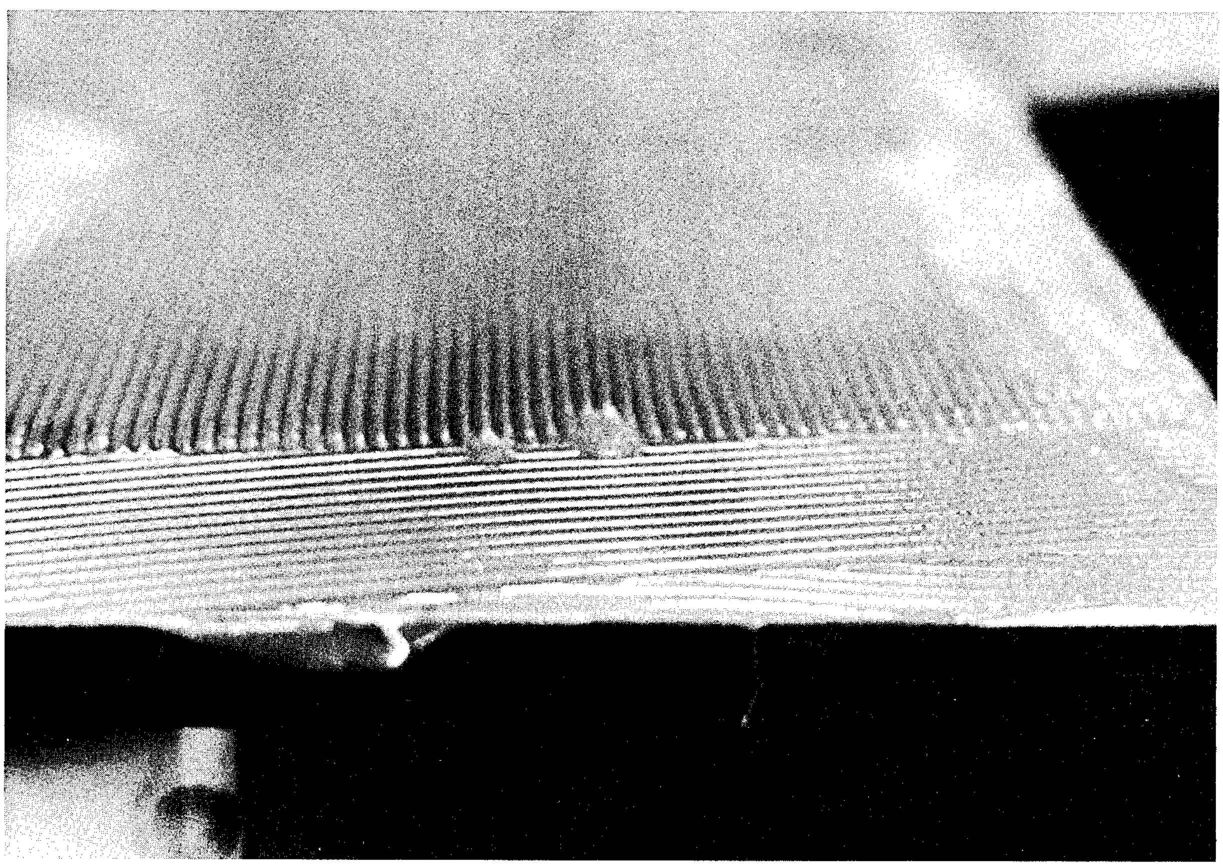


Fig. 1.4

Fig. 1.5

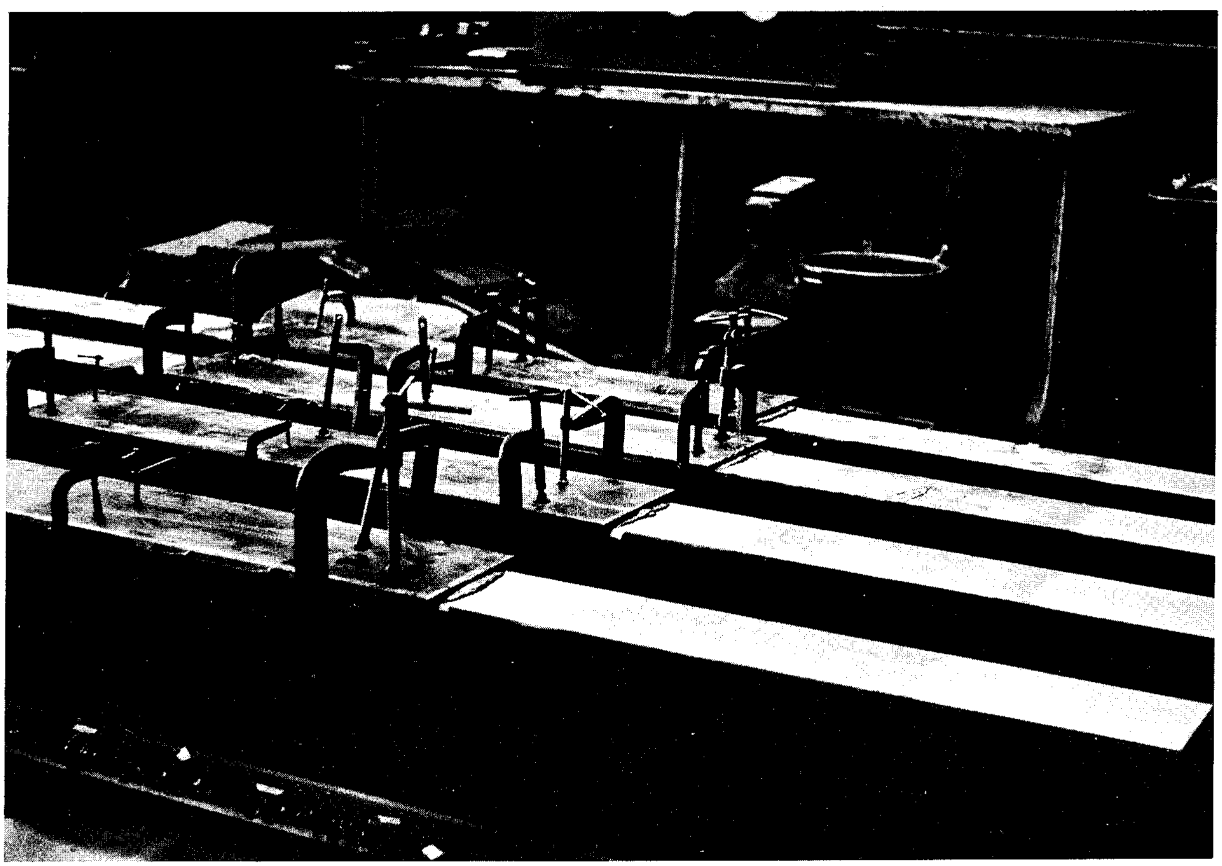


Fig. 1.6

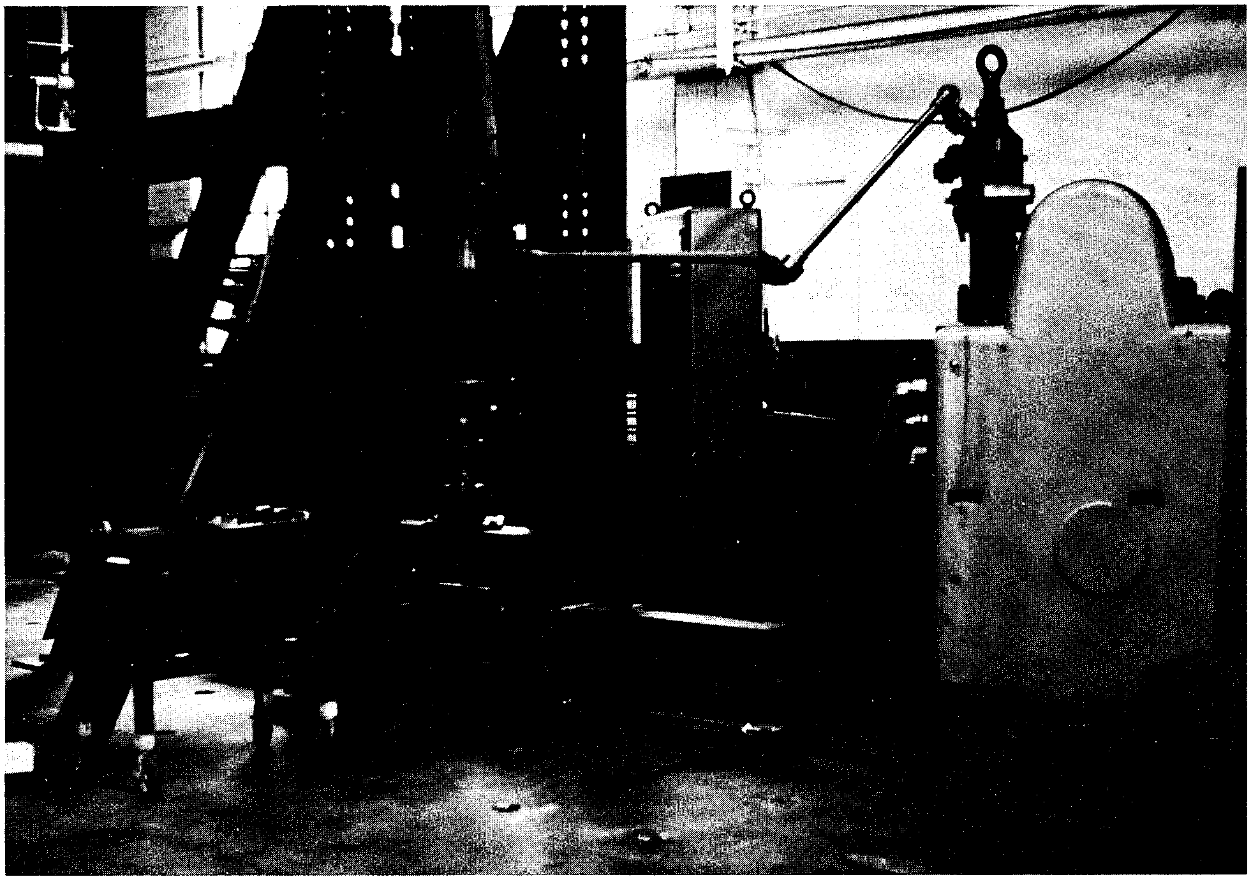


Fig. 1.7 Fatigue Test Fixture

Fig.1.8 indicates that flexure plates were used as lateral restraints. Those restraints and all bearing plates were bonded on the specimens using Lord Versilok 201 modified acrylic adhesive with the same surface preparation and curing procedure as used with the cover plates.

The strain range was obtained by a strain gauge on the flange of the beam as shown in Fig.1.9. The strain range was set so that the stress range at the edge of the cover plate was as required.

The following test sequence was used. A static load/deflection curve was obtained first to determine the effectiveness of the adhesive in developing the stress in the cover plate. The beam was then subject to constant amplitude, sinusoidal fatigue loading. If the beam survived the desired number of cycles, the static test for the load/deflection curve was repeated.

As in the Fisher research, the stress range in the extreme fibers of the beam at the ends of the cover plates was controlled. In that work, the maximum stress range without utilizing load reversal was 20 ksi (2 ksi minimum stress; 22 ksi maximum stress). Since the objective was to demonstrate the ability of adhesives to improve fatigue lives of the primary beams this most severe stress range was selected for the adhesively bonded specimens.

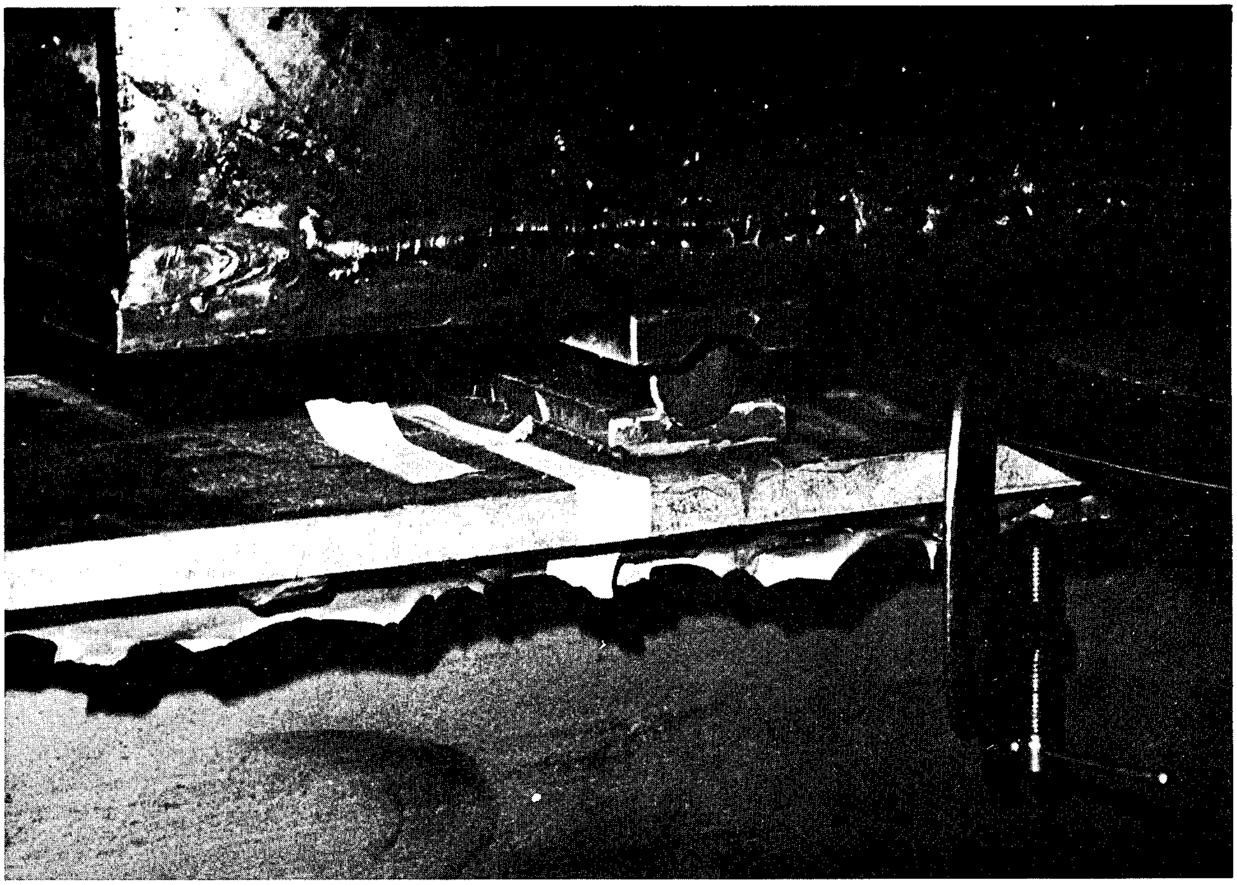


Fig. 1.8 Bearings and Lateral Restraints

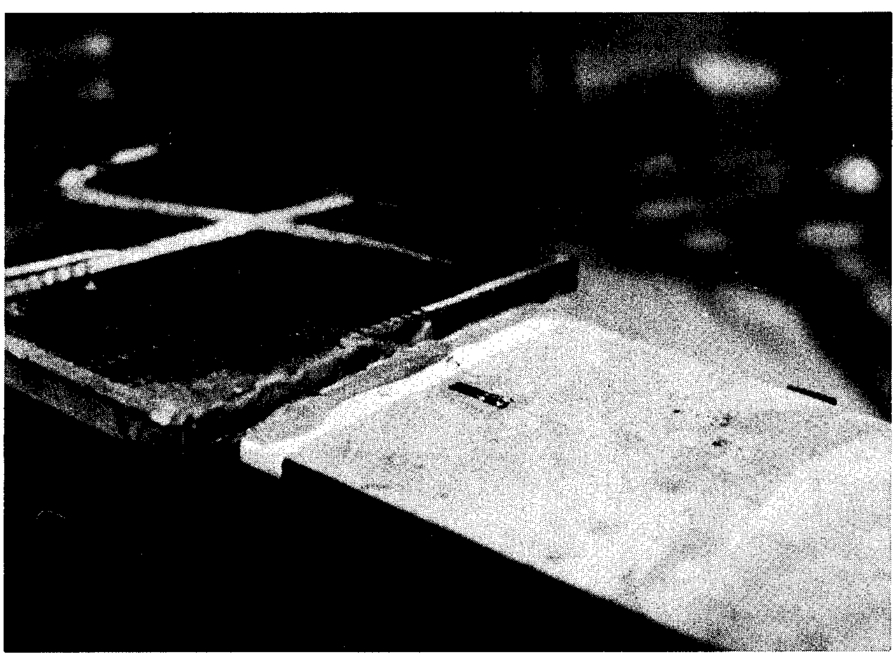
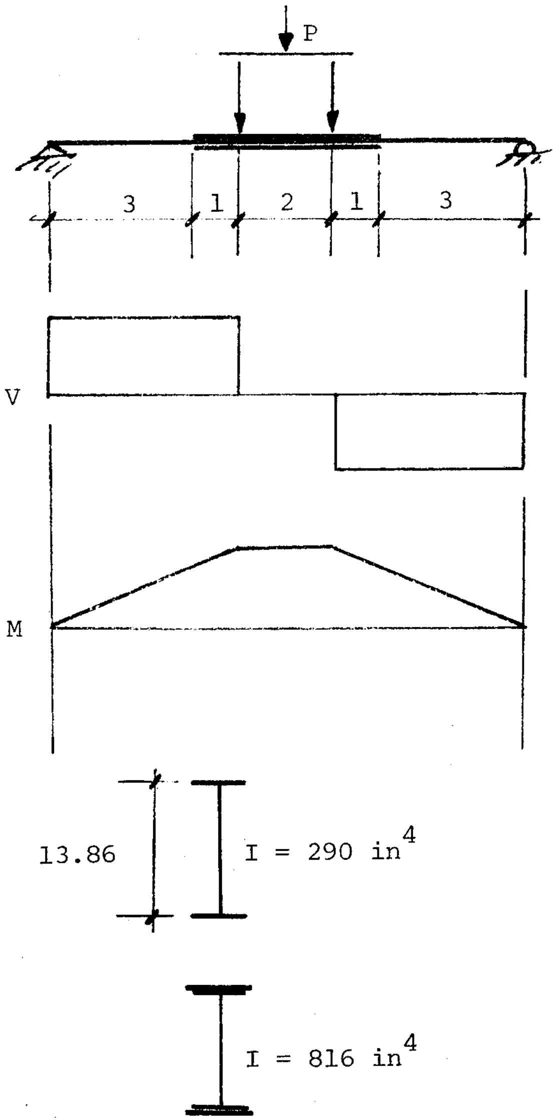


Fig. 1.9 Strain Gauge to Control Stress Range

Nominal forces and stresses were as follows:



$$P_{max} = \frac{22(41.9)(2)}{36} = 51.2\text{k}$$

$$P_{min} = \frac{2(41.9)(2)}{36} = 4.66\text{k}$$

Maximum flexural stress at mid-depth of cover plate

$$\sigma = \frac{51.2}{2} \; \frac{(48)(6.93 + .28)}{816.3} = 5.43 \text{ ksi}$$

Maximum total force in cover plate

$$F \simeq 5.43 \left(\frac{9}{16} \times 9\right) = 27.5\text{k} \qquad (1.1)$$

Nominal adhesive shear stress (over 12" development length)

$$\tau \simeq \frac{27.5}{12(6.733)} \simeq 0.340 \text{ ksi} \qquad (1.2)$$

Such a nominal stress is not an unreasonable working shear stress for an adhesive. The equilibrium stated in Eqs.1.1 and 1.2 may be used to obtain a preliminary estimate for the length required to develop a cover plate by adhesives. For example, assuming a cover plate equal in width to a flange then to develop 24000 psi in a 1" thick cover plate requires 48" of bonded length at a nominal shear stress of 500 psi.

As control for the steel in the beam, the tensile specimen shown in Fig. 1.10 was tested. The results, indicated in Fig.1.11, show that the

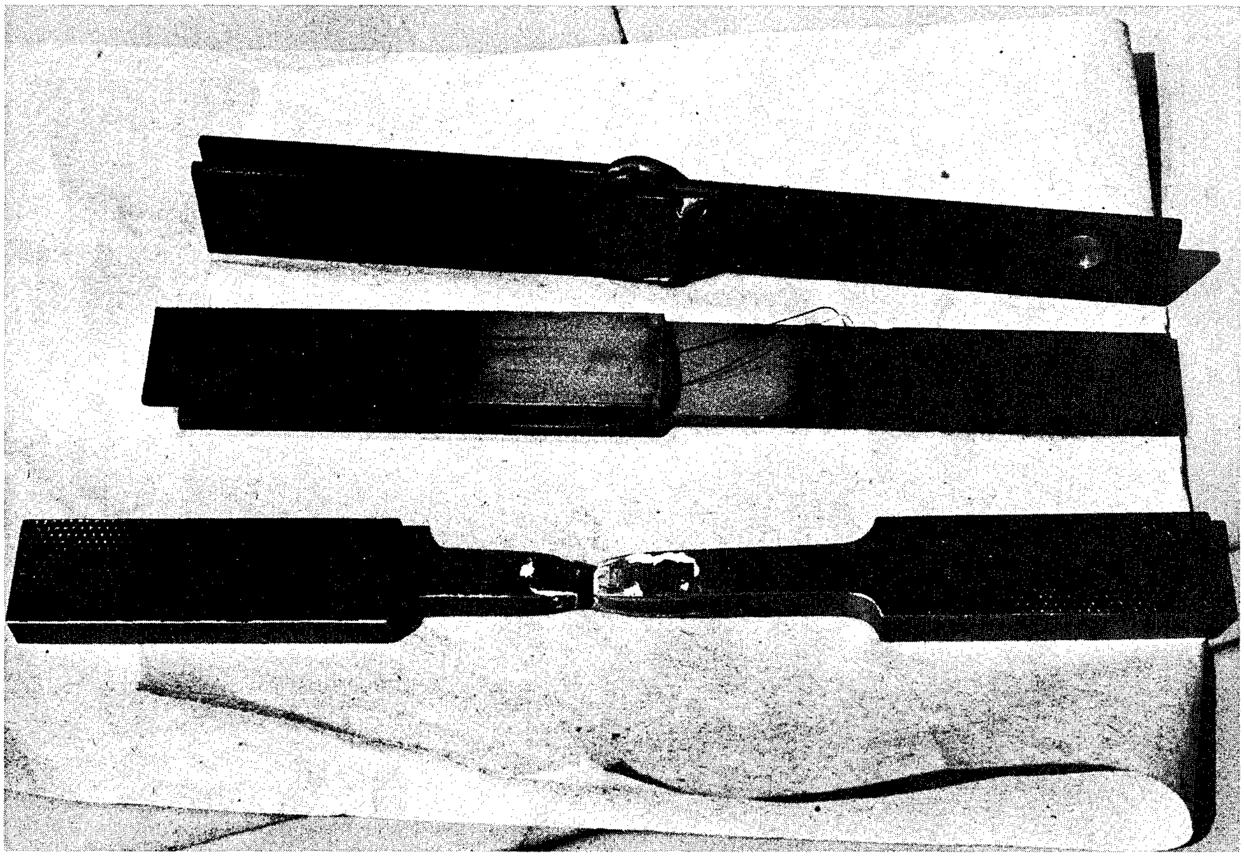


Fig. 1.10 Tensile Specimens

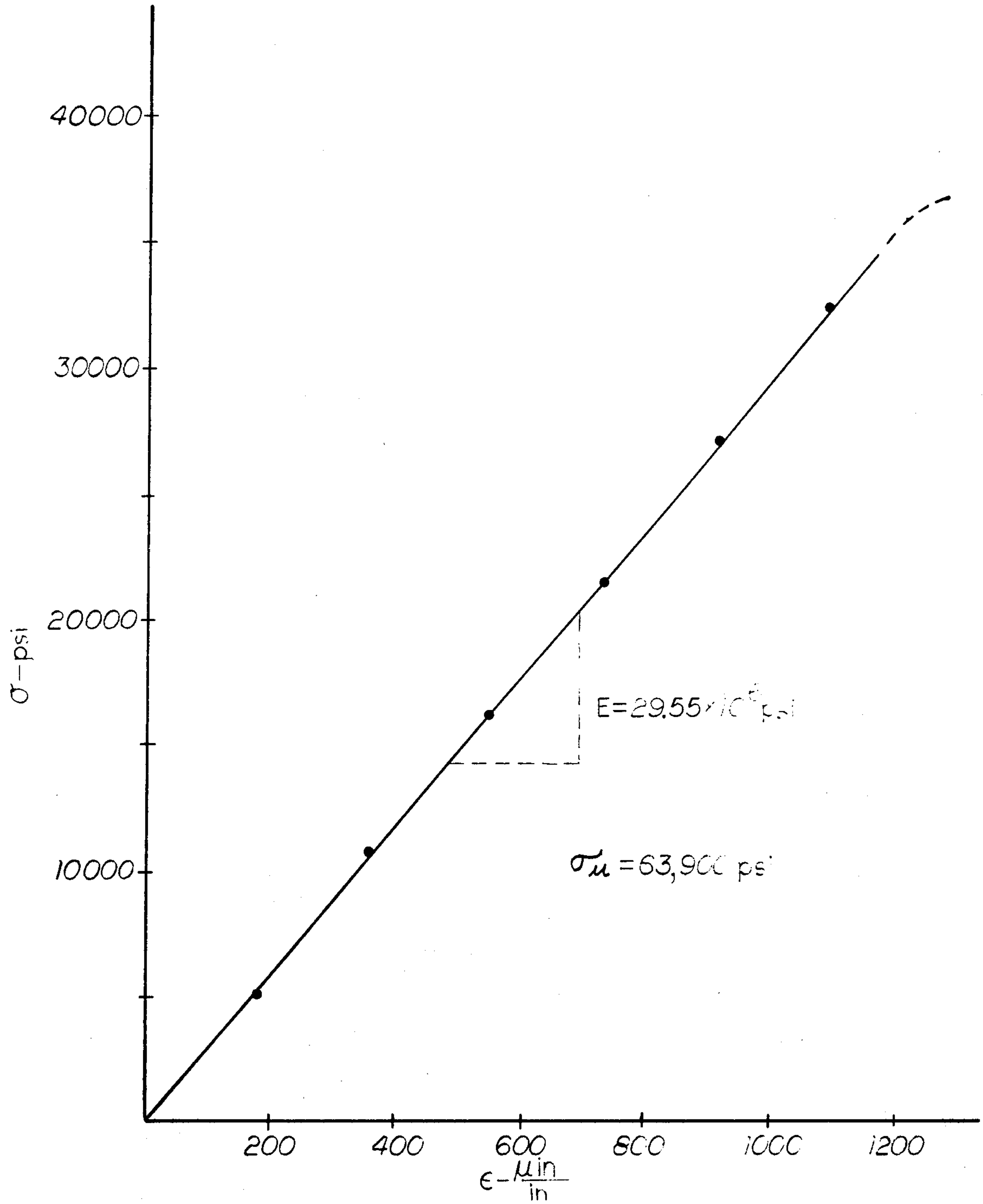


FIG. 1.11 STRESS–STRAIN CURVE FOR STEEL OF LARGE SCALE FATIGUE SPECIMENS

tensile strength was within the ASTM allowable limits and that the modulus agreed with accepted values. Six double lap shear specimens of each of the two adhesives were also prepared during fabrication of the cover plated beams and subsequently tested. One of the specimens from each adhesive was rejected because of excessive eccentricity. Table 1.1 gives the shear strength data as well as the nominal average shear strengths. The failures on the EA934 were primarily adhesion while for the Lord Versilok 201 they were partially cohesive and partially adhesion failures.

Specimen	EA 934 Epoxy	Lord Versilok 201 Modified Acrylic
1	4480	5285
2	3420	4555
3	4440	4620
4	2210	5030
5	2090	4960
Avg.	3328 psi	4890 psi

Table 1.1. Double lap shear strengths (1/2" lap, 1 in^2 total bonded area) for adhesives used in fabricating bonded, cover plated beam specimens.

Before describing the results from the testing of the bonded beams. it is useful to review the most important results from Fisher's [87] study

of rolled beams with welded cover plates. Overall his study showed that stress range is a dominant factor affecting the fatigue life of beams. Fig.1.12 shows results for rolled beams with cover plates wider than the flange with and without welds at their ends. It indicates that beams whose cover plates are not welded at their ends have the smallest fatigue lives. Fig.1.13 (from) Ref. 71) summarizes Fisher's [87] work by graphically demonstrating the lower fatigue lives of beams with welded cover plates when compared with plain rolled or welded beams. To be noted is the fact that the welded cover plated beams, for a stress range of 20,000 psi have fatigue lives ranging from 100,000 to 300,000 cycles.

The following test histories were recorded for the four specimens tested.

Lord Versilok 201 - Beam #1

- 2.2×10^6 cycles with no visible damage. Test shut down. Load deflection test performed and fatigue testing resumed.
- 3.2×10^6 cycles - Initial debonding observed at the bondline in position 1 in Fig.1.15
- 3.3×10^6 cycles - Initial debonding observed at the bondline in position 2 in Fig.1.15
- 6×10^6 cycles - Fatigue test terminated, debonding has arrested (at approximately 5"-6" in length at both locations); debonded areas are not propagated across the entire flange width. No damage noted in steel. Static load deflection test is run.

Fig. 1.14 compares the static load deflection curves obtained after 2.2×10^6 cycles and 6.0×10^6 cycles with the theoretical bounds of a fully active cover plated beam and a plain W15x30 beam. It is to be noted that the steel and the adhesives survived 3.2×10^6 cycles with no damage. This fatigue life is an order of magnitude better than that found for welded

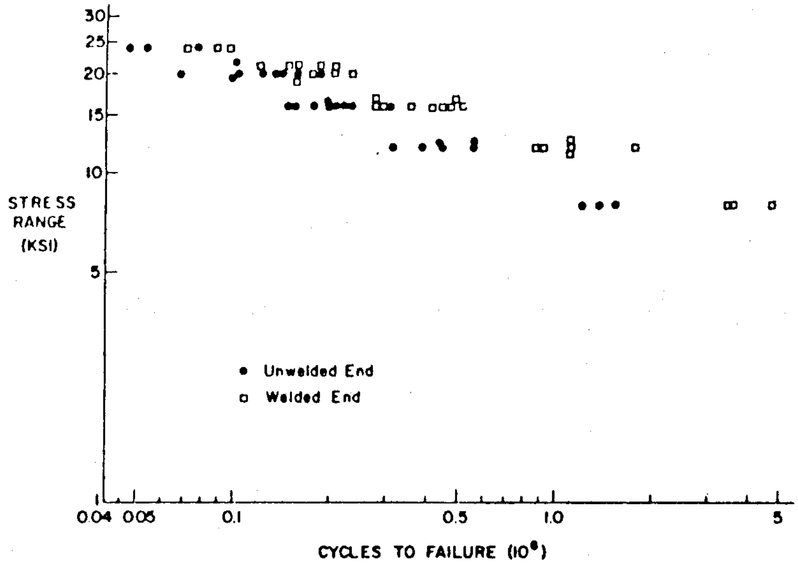


Fig. 1.12 Comparative fatigue strength for beams with cover plates wider (CB) than the beam flange (from Ref. [71])

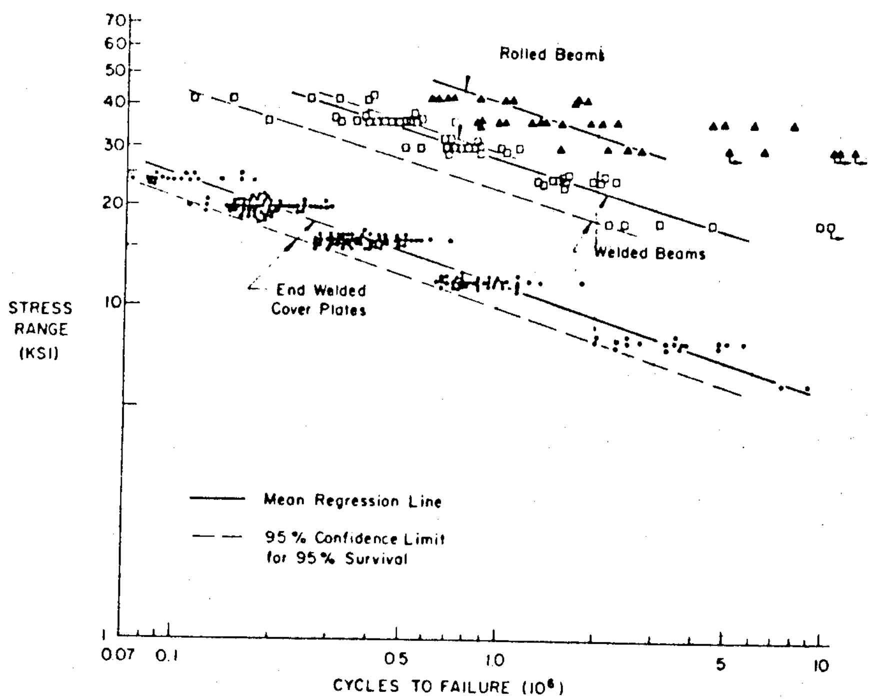


Fig. 1.13 Mean fatigue strength and 95 percent confidence limits for rolled, welded, and cover-plated beams. (From Ref. [71])

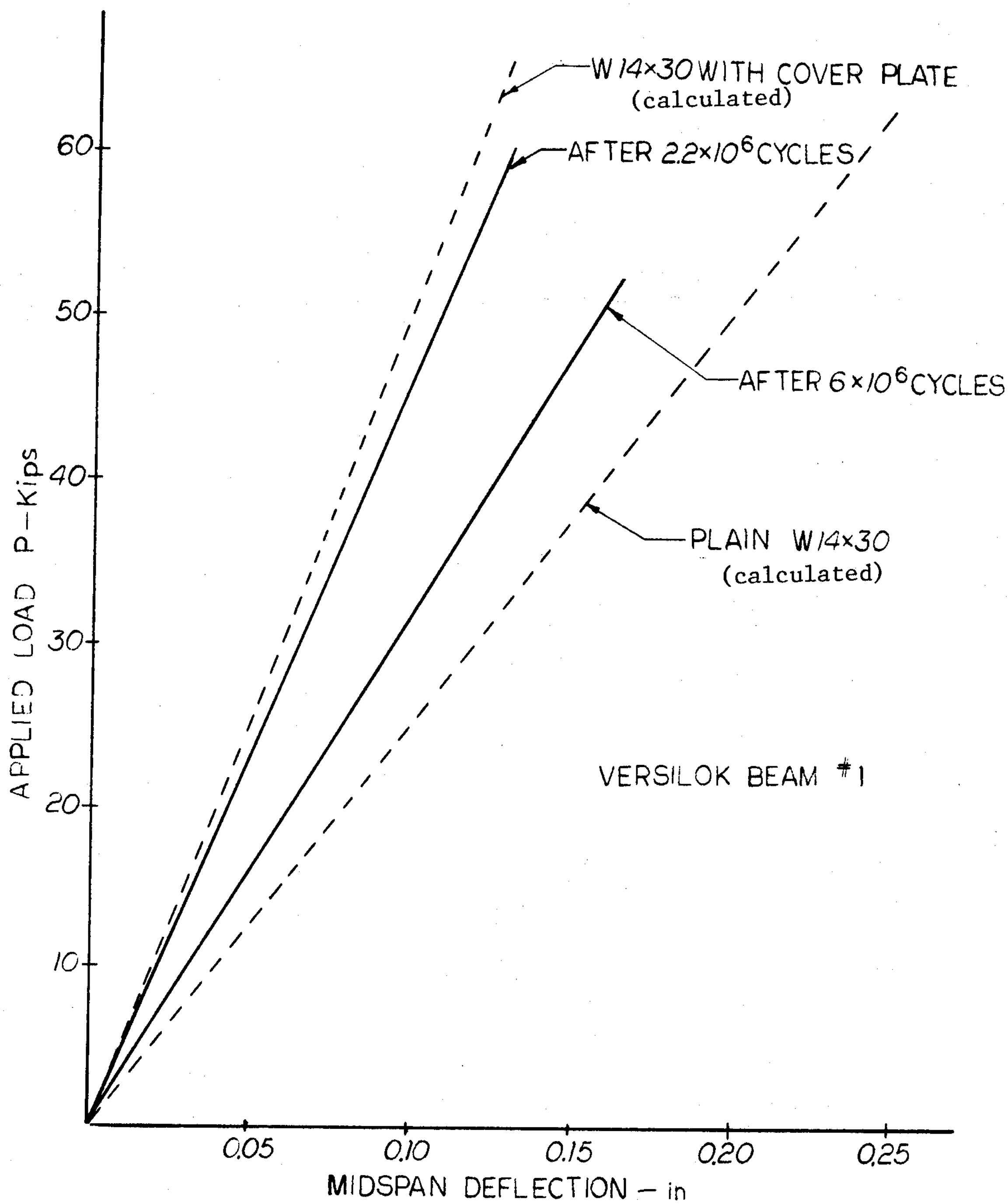


FIG. 1.14 STATIC LOAD DEFLECTION CURVES

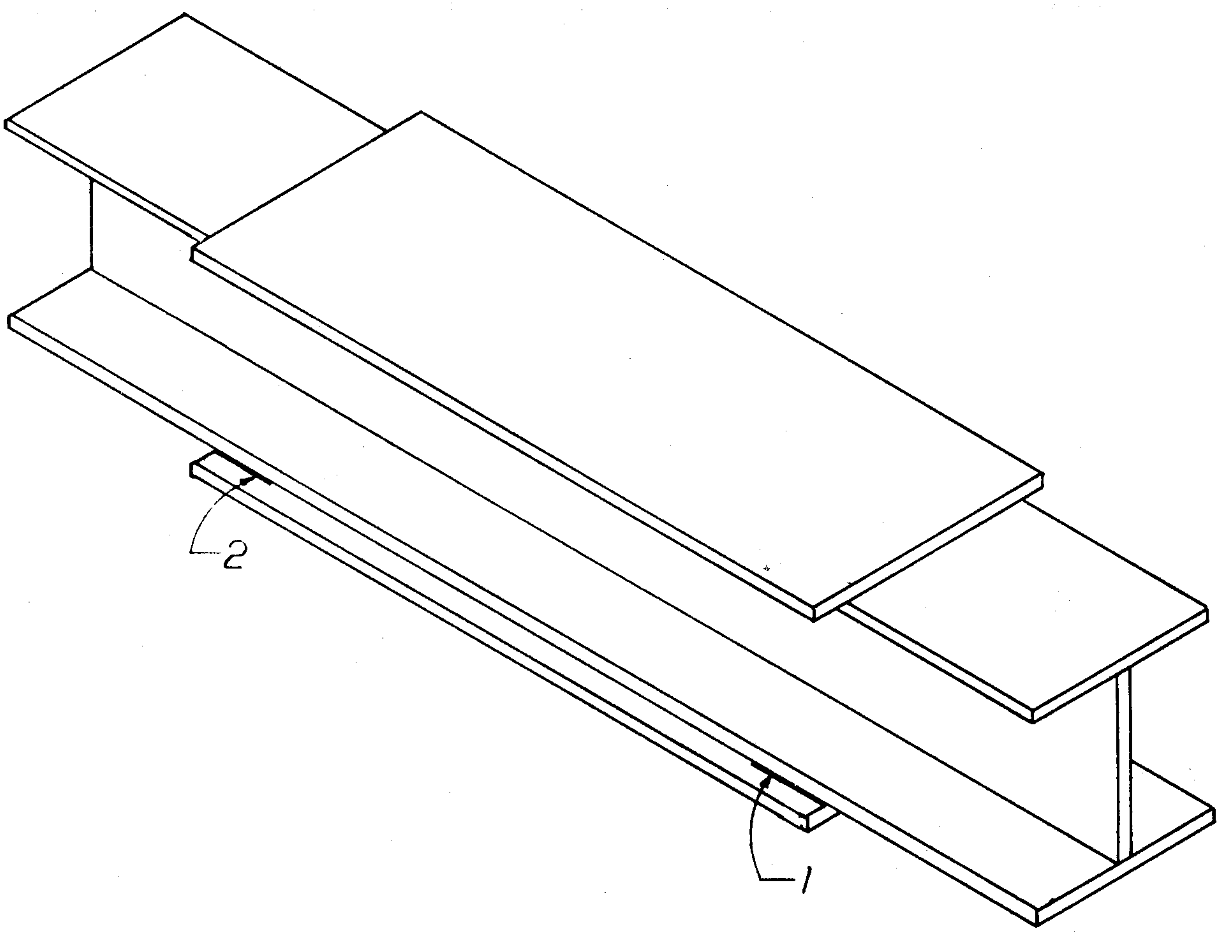


FIG. 1.15 LOCATIONS OF PARTIAL DEBONDING

cover plated beams (see Fig. 1.13). Also significant is that the debonding was arrested and that the cover plates were active after 6×10^6 cycles. No fatigue cracks were observed in the steel at the end of 6×10^6 cycles. It is hypothesized that the partial debonding occurred because of residual tensile stresses in the adhesive that were placed when the plate was bonded to the beam and held in place with clamps (as seen in Fig. 1.6).

Lord Versilok 201 - Beam #2

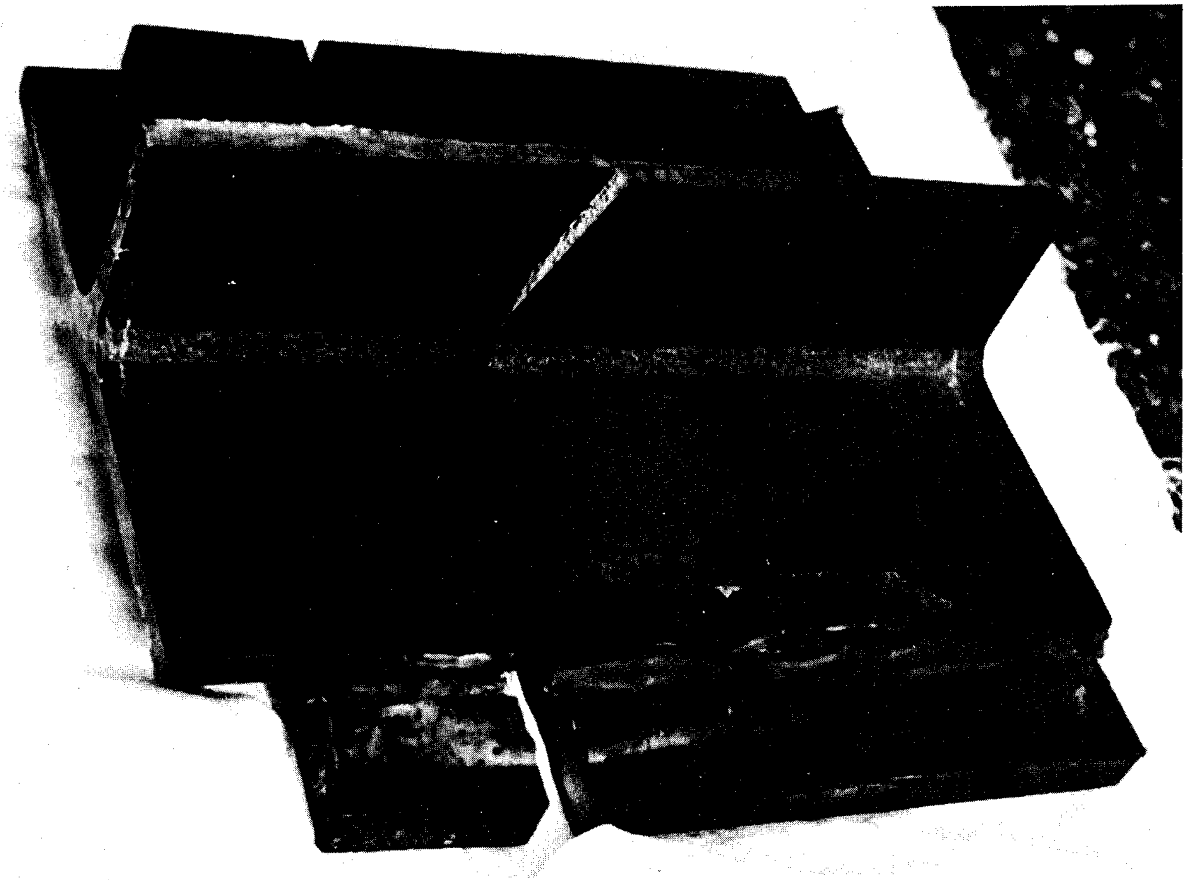
- Static load deflection test. Fatigue test begun
- 3.25×10^6 cycles. Initial debonding at position 1 of Fig. 1.15
- 3.5×10^6 cycles. Test terminated; cracked flange in W14x30 beam. (See Fig. 1.16)

To determine the origin of the steel fatigue failure, sections of the beam were submitted to a metallurgist for examination. The origin was found at a slight edge imperfection which existed in the tip of the flange of the rolled beam (see Fig. 1.17). Because of the presence of the imperfection, and because the failure did not occur at the ends of the cover plate or where some debonding had occurred, it is believed that the steel failure was not caused by stress concentrations induced by the adhesive.

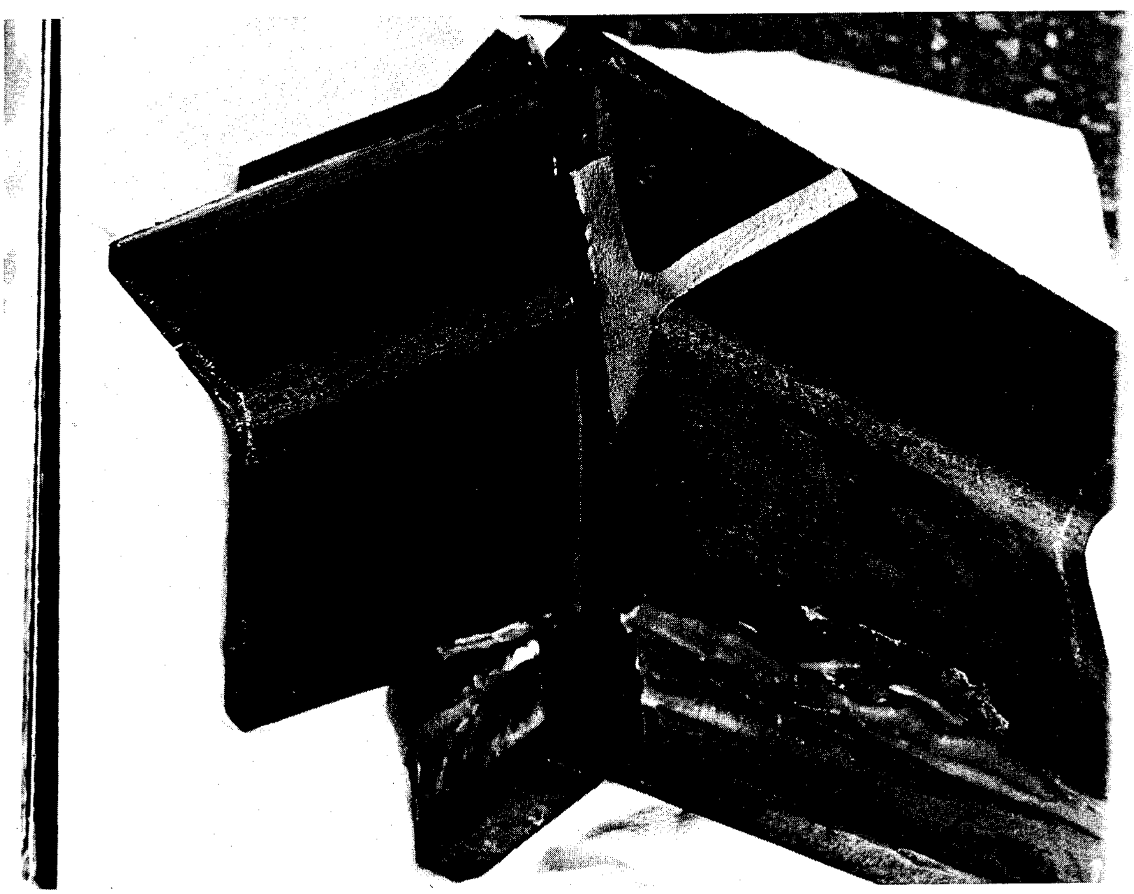
Dexter-Hysol EA 934 - Beams #1 and #2

Both beams failed during the static load-deflection tests at loads between 49 kips and 56 kips which correspond to adhesive nominal shear stresses of 303 psi and 346 psi. The double lap shear strength data given in Table 1.1 indicates that such shear stresses should be resisted by the adhesive. However, some residual tensile stresses may have been placed in the adhesive by the bonding/clamping process. It is likely that the adhesive failed because of combined shear and tensile stresses.

Fig. 116 Fatigue Crack in Beam



(a)



(b)

Fig. 1.17 Sectioned Portion of Cracked Beam

To repeat, the primary objective of the fatigue tests was to show that adhesive bonds, while performing a structural function, do not adversely affect the fatigue life of rolled steel sections. A full stress/fatigue life curve for the adhesive was not sought. Therefore a complete set of specimens for various stress ranges was not tested. The following specific conclusions can be made from the large scale tests that were conducted.

Beams Bonded with Lord Versilok 201 Modified Acrylic Adhesive

The adhesive did perform the structural function of fastening the cover plates. The bonds on both beams survived over 3×10^6 cycles of nominal shear stress range of 309psi without failure; only localized bonding failures were evident on the beam subjected to 6×10^6 cycles. The steel beams with bonded cover plates did survive 6×10^6 and 3.5×10^6 cycles at a stress range of 22 ksi. The fatigue failure which occurred in one beam at 3.5×10^6 cycles originated at a slight edge imperfection; it was not caused by the presence of the bonded cover plate. Comparing these results with those of Fisher [87] for cover plated beams, it can be inferred that indeed, adhesive bonds as substitutes for certain welded details, can improve the fatigue life of structural members.

It is hypothesized that the local bondline failures were caused by tensile stresses which were placed in the adhesive by the removal of clamps after the bonding process. For the imposed stress conditions, the failure mode was not brittle; the debonding was arrested.

Beams Bonded with Dexter-Hysol EA 934 Epoxy Adhesive

Although the nominal shear stress in the adhesive was well below its

measured double lap shear strength, adhesion failures occurred during the static load/deflection tests. Again, it is believed that tensile stresses were placed in the adhesive by removal of the clamp forces. Apparently, the strength of this adhesive is very sensitive to tensile stresses. <u>Other epoxies may, of course, have quite different performance characteristics.</u>

As noted previously, all bearings (see Fig.1.8) were bonded with Lord Versilok 201. All bearings performed very well, with no failures. Fig. 1.18 shows bearings removed after 6×10^6 cycles of nominal maximum bearing stress equal to 1733 psi or $\left(\frac{52000 \text{ lbs}}{(2.5\text{in.} \times 6\text{in.})}\right)$. Degradation of the adhesive was visible in the area under the web where the actual stresses were much greater than nominal.

Also all flexure plates used as lateral restraints (see Fig. 1.8)were bonded with Lord Versilok 201. Although the required lateral restraining forces are difficult to estimate, maximum shear stresses were on the order of 50-100 psi. No degradation of such bonds was observed in either beam after 6×10^6 and 3.5×10^6 cycles.

In summary, the tests indicated that steel to steel bonded connections as substitutes for certain welded details have the potential for improving fatigue lives and therefore should be studied further.

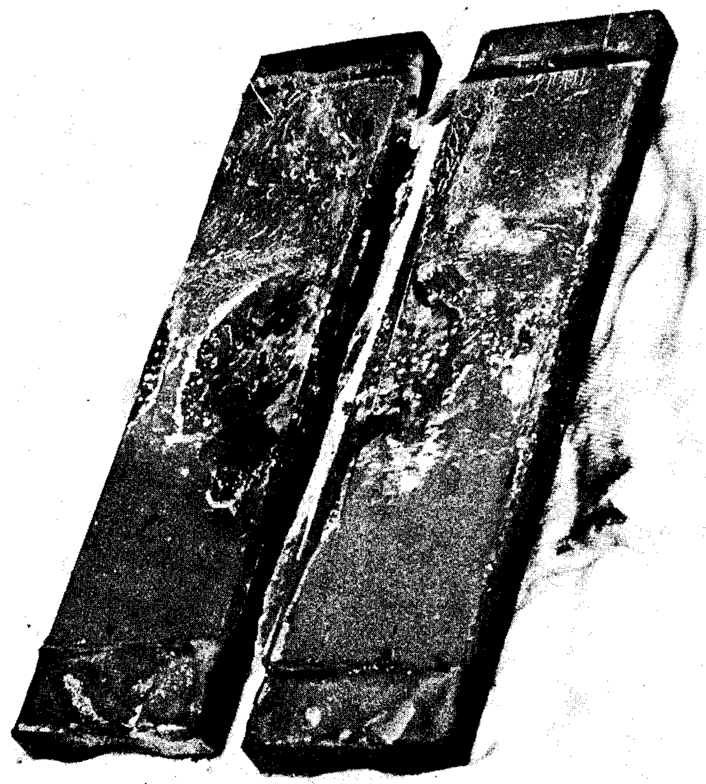


Fig. 1.18 Bearing Plates after 6×10^6 Cycles

CHAPTER II

Bridge Applications and Performance Criteria

The experimental results of Chapter I indicated that, as a method for improving the fatigue life of bridges, adhesive bonds merit further investigation. Their overall feasibility, of course, depends on whether they can satisfy a set of performance criteria; performance criteria defined by the envisioned applications. This chapter attempts to define those uses so that some preliminary performance specifications, analogous to those which exist for other structural materials, can be established. Moreover, for satisfactory performance of adhesive bonds on bridges, specifications must be written not only for the adhesive materials but also for surface preparation, adhesive application and curing procedure.

Broadly, the following areas are significant for satisfactory performance.

Stress-Strain Behavior of Adhesive - Valid constitutive equations (i.e. elastic, viscoelastic, etc.) must be established and material constants such as E, ν, viscosity,etc. must be quantified. The material models and their constants are required to compute stress conditions in a bond area and the changes in such stress conditions due to shrinkage, creep or temperature variations.

Static Strength of Bond - A bonded connection may be visualized as a series system which fails when the weakest of the following two "links" fails:

1) Adhesive material (it is assumed that failure in the adherends is precluded) - a cohesive failure

2) Adhesion failure at the adherend-adhesive interface

The relative strength of the two links can vary with time. For example, the adhesion between steel and some adhesives may degrade in certain environmental conditions.

In addition, adhesives in thin layers (between steel adherends) are almost never in one-dimensional stress states. Therefore at least a two-dimensional strength theory is required for the adhesive material. The adhesive strength obtained from one-dimensional tensile tests of bulk adhesive specimens is most likely an inadequate strength measure. In summary, satisfactory static strength in a bond requires understanding and controlling:

1) surface preparation
2) application and curing of adhesive
3) strength of adhesive (or cohesive strength) and its changes under a specified design environment (e.g. temperature, moisture, salts, oils, acids, etc.)
4) strength of adhesion and changes under a specified design environment

Fatigue Strength - On bridges, connections generally experience cyclic stresses from both gravity loads and thermal cycles.

Fracture Toughness - The strength of bonds must not be flaw-sensitive within the range of operating temperatures and under various stress conditions.

The state-of-the-art in establishing constitutive equations for adhesive materials will be reviewed in Chapter IV. The relative importance of various properties and the actual strength levels required to achieve reasonable connections vary with intended uses. A fundamentally important distinction can be made between "short term" and "long term" projected uses; e.g. between temporary construction attachments to girders and permanent

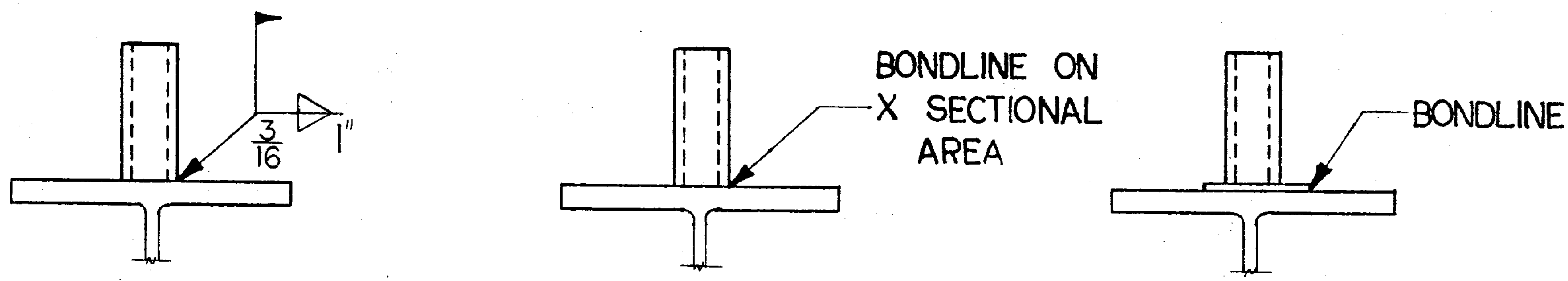
attachments like vertical stiffeners; the durability requirements for the two uses are quite distinct.

The following section describes some potential applications for the purpose of defining some performance bounds. Some representative applications may be as follows:

1) Supports for concrete deck finishing machines. Fig.2.1 shows a welded detail for a rail support. It is inferred that the primary force on the support is a vertical gravity load, although the machine may cause some horizontal thrust. Bearing is probably the primary load transfer mechanism. As detailed, the two 3/16" fillet welds have an allowable shear (assuming A-36 steel, E-70 electrodes, shielded-metal-arc welding) of approximately 5.5 kips. That shear force can easily be transferred by an adhesive bond, perhaps even without a cap plate. The durability requirements for such a temporary support detail are not significant.

2) Sign Support. Fig.2.2 a shows a portion of a sign support which is attached to the primary beam member. Assuming a 3 kip allowable shear in the bolt and an allowable nominal tensile stress of approximately 150 psi in the adhesive, then a 7" length of a WT section having a 3" wide flange would provide approximately the same load transfer capacity. Perhaps a more compact bonded connection may be achieved by placing the WT section on the flange so as to transfer force by adhesive shear stresses (although bending is introduced). The adhesively bonded connection will have to satisfy durability requirements.

3) Intermediate Stiffeners. Intermediate stiffeners must be sufficiently rigid with respect to the midthickness of the web to keep the web at the stiffener from deflecting out of plane when buckling of the web occurs. (See Fig. 2.3)



A) WELDED DETAIL

B) BONDED DETAILS

FIG 2.1 SUPPORT FOR DECK FINISHING MACHINE

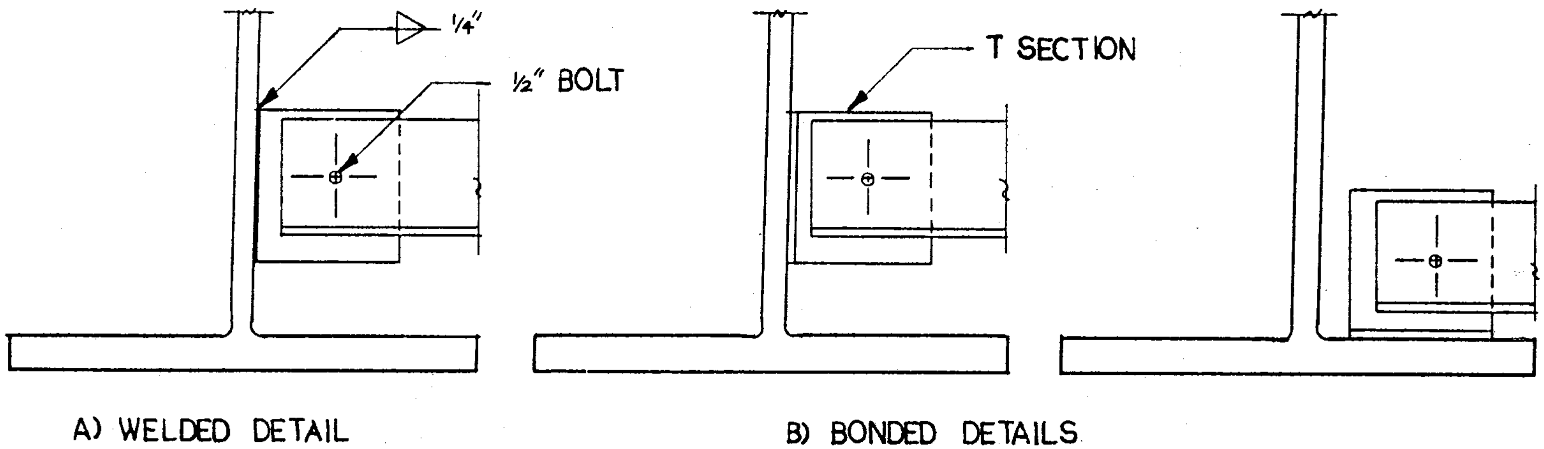


FIG 2.2 SIGN SUPPORT

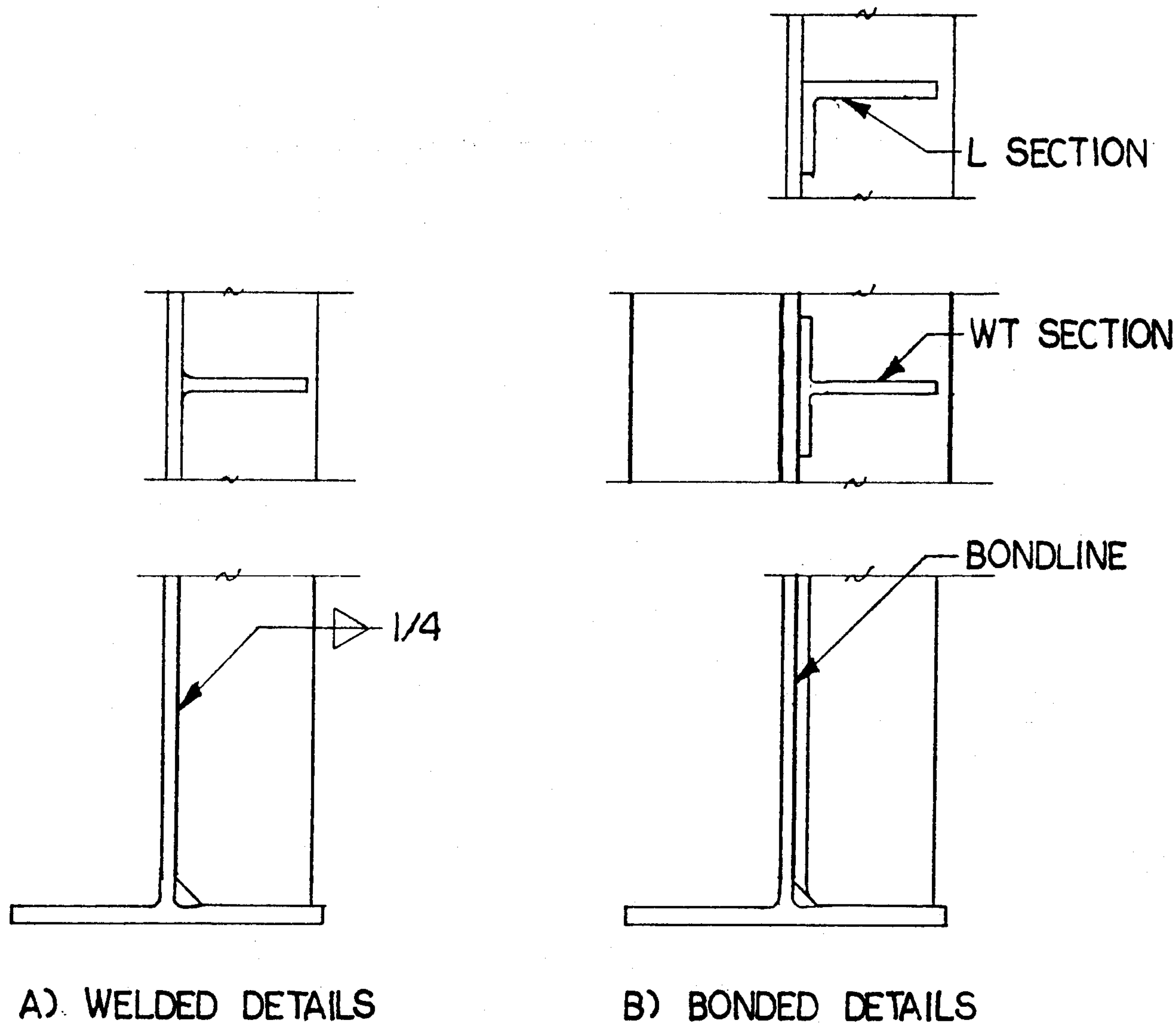


FIG2.3 BONDED INTERMEDIATE STIFFENERS

Considering tension field action, intermediate stiffeners must also have an area sufficient to carry compressive forces. The shear stress transferred at the connection between the web and the stiffener and therefore the required strength of the connection is unknown. However, the AISC Specifications do provide an equation (AISC Formula 1.10-4) which gives a design shear flow for the connection. For A-36 steel and for web heights from 40" to 70" the design shear flows vary from 1.38 kips/in to 2.41 kips/in respectively. Assuming an allowable nominal adhesive shear stress of 500 psi, the shear flows imply bonded widths of 3" to 5" in the longitudinal direction of girders.

Noting that the girder is subjected to flexural stress cycles, it seems that to minimize transfer of flexural stresses into the bonded segment of the angle or tee section, the thickness and the width (along the longitudinal direction of the girder) of the bonded segment should be minimized. Also a thicker bondline may decrease flexural stress transfer, although it may also decrease the bond strength. (See also Fig. 5.9).

The bonded stiffener connection must be durable under gravity load and thermal stress cycles as well as under bridge environmental conditions. Stiffeners attached to cross frames, diaphragms, or floor beams have, of course, quite different strength requirements.

4) <u>Lateral Bracing Connections</u> (Fig.24) Lateral bracing generally must have a capacity equal to approximately 1-5% of the strength of the compressive part of a flexural member. Occasionally maximum slenderness ratios determine minimum sizes of bracing members. Typical sections used are WT 6x13.5 or L3x3x5/16 connected at their ends with 1/4" fillet welds. From estimates of the allowable tensile forces in such sections and from the capacity of a connection assumed as 12" of 1/4" fillet weld, it is inferred that a bonded connection would be required to develop forces roughly ranging from

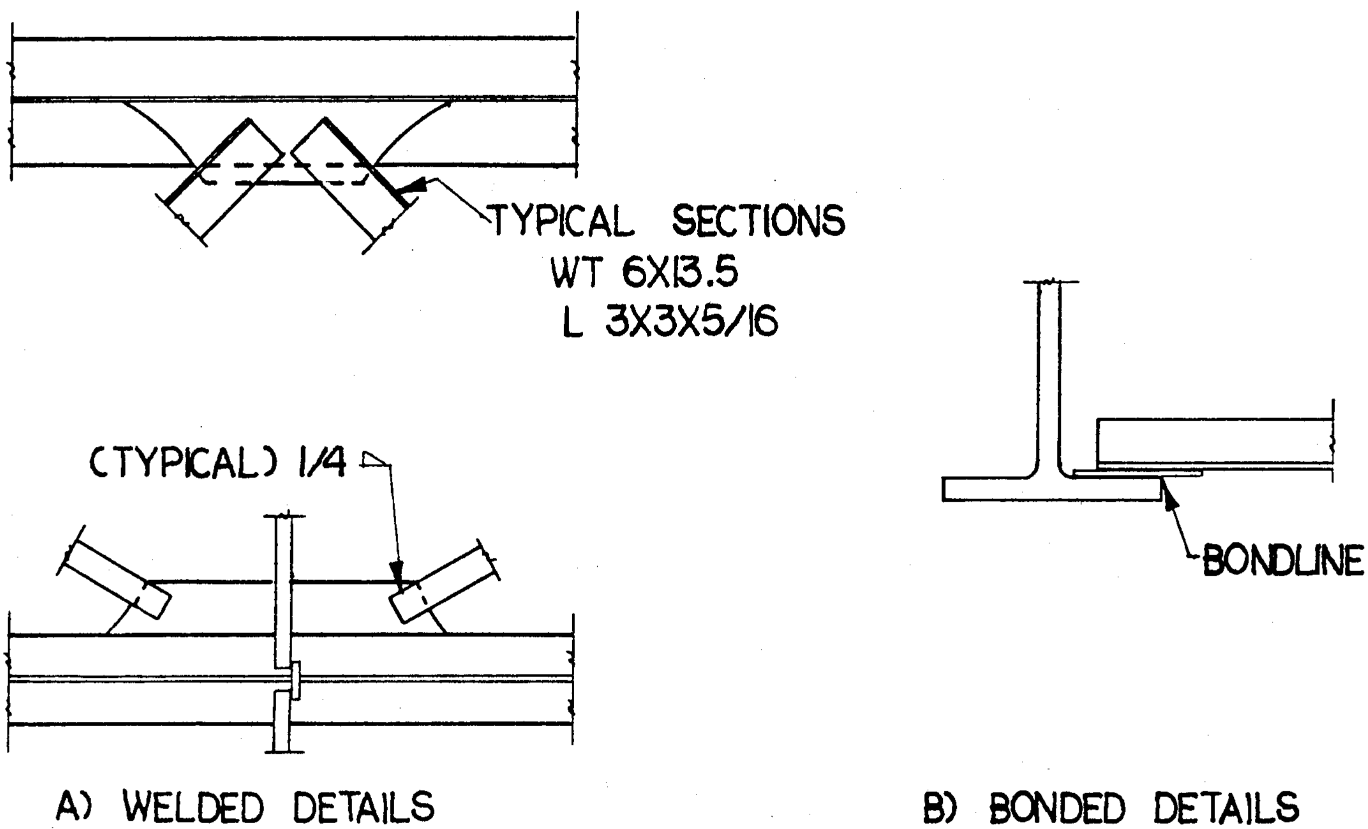


FIG. 2.4 CONNECTIONS FOR LATERAL BRACING

40 kips to 80 kips. Assuming an allowable adhesive shear stress of 500 psi implies that the required bonded area may range from 80 in^2 to 160 in^2. As for vertical stiffeners, the durability of the bonded lateral bracing connection during flexural stress cycles of the girders as well as other conditions must be assured.

5) Scupper Support (Fig.2.5) Although a scupper pipe may not exert a heavy load, the eccentricity of the load means that the bonded connection must resist primarily a bending moment. A more effective bonded detail might have to be developed so that the adhesive is stressed primarily in shear.

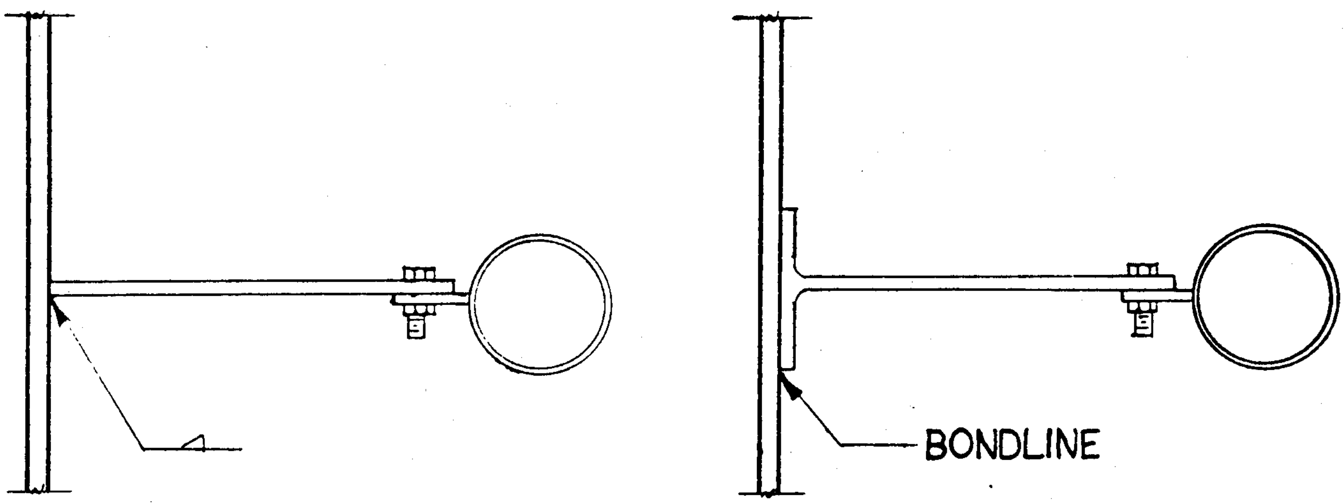
A multitude of other applications for adhesives on bridges may be envisioned. The few examples cited indicate that:

i) Assuming allowable adhesive stresses of 150 psi in tension and 500 psi in shear yields bond areas having a feasible size.

ii) "Pure shear" conditions are not always attainable. Therefore the strength of connections under combined shear and tensile forces and bending moments must be known either from experimental data or from analytical predictions.

iii) It should be verified that bonds are durable given the cyclic interaction of a bonded plate with a primary flexural member.

Having briefly examined areas important for satisfactory bond performance and some representative uses of adhesives on bridges, the formulation of adhesive material performance specifications may be considered. In this respect, it is useful to review first Federal Specification MMM A-134 which applies to epoxy resin adhesives used for metal to metal structural bonding.



A) WELDED DETAIL B) BONDED DETAIL

FIG. 2.5 SCUPPER CONNECTION

The overall organization and scope of that Specification is as follows. It states first that the adhesive must not be corrosive to the metal surfaces. It then gives acceptable bounds on working characteristics and mechanical strength properties under various environmental conditions. The following properties are considered as "working characteristics".

i) storage life of adhesive components

ii) consistency (viscosity) and working or pot life of adhesive mixture

iii) curing temperature, pressure and rate

and the following mechanical properties are bounded

i) "cleavage" strength - (ASTM D1062-78)- a measure of fracture toughness

ii) tensile shear strength

iii) creep-rupture strength

iv) fatigue strength - An adhesive must survive 10×10^6 cycles (at 60 hz) at a specified stress level

Minimum mechanical properties are specified for some or all of the following environmental conditions

i) Low, (-67^{o}F), room and elevated (160^{o}F-180^{o}F) temperatures

ii) salt water spray

iii) fluid (water, isopropyl alcohol, hydraulic fluid) immersion

iv) accelerated weathering (Fed Test Method Standard No. 141)

All strength values except "cleavage" are determined from single lap shear specimens. Chapter V discusses the relevance of such a test to the strength of other bonded joints. The Specification does not directly set specific

bounds on:

1. elastic/viscoelastic material constants
2. cure shrinkage
3. diffusivity of water in adhesive
4. thermal properties

The preceding discussion and comments indicate that performance specifications for bridge adhesives should include requirements in the following areas.

1) Handling and Application

a) Storage - Probably a room temperature storage is feasible, although the 1-year shelf life required by MMM-A-134 may be unnecessary.

b) Surface preparation - The adhesive should develop adequate strength with minimum surface preparation. Sandblasting,solvent wiping and perhaps priming are attainable on bridges. Etching, anodizing and other more demanding surface preparations are perhaps impractical.

c) Consistency of uncured adhesive - The adhesive should have good gap filling properties because of the character of the surfaces of rolled or fabricated sections. However, a liquid or a near liquid adhesive may not be desirable.

d) Bonding and curing - An adhesive which can cure rapidly at room temperature and with only nominal pressure is perhaps most convenient.

2) Design Environmental Conditions. The categories specified in MMM-A-134 are appropriate. The exact values of the temperature extremes or the lengths of time for salt spray or fluid immersion may have to be adjusted.

3) Adhesive Material Properties in Design Conditions

a) Non corrosive

b) Limited curing shrinkage

c) Low Diffusivity of water

d) Stress-strain properties - bounds on elastic moduli and viscosity (creep and relaxation) may be appropriate

e) Thermal properties compatible with steel.

4) <u>Steel to Steel Bond Properties in Design Conditions</u>

a) Bond static strength. Minimum strength in shear, tension and combined shear and tension must be assured. Strength variability must be within acceptable statistical bounds. Strength must be attainable at bond line thicknesses of approximately 0.01". The sensitivity of the strength to bondline thickness variations should be small.

b) Bond fatigue strength

c) Bond fracture toughness

d) Bond durability in weathering conditions - The degradation of the strength properties through diffusion of water in the bondline or by other weathering mechanisms should be limited.

Within the above general performance requirements, the applicability of available adhesives can be examined.

CHAPTER III

Adhesives and Bonding Procedures

Numerous adhesives are available to satisfy a variety of industrial needs. Although there are no generally accepted schemes for classifying adhesives, the terms "structural adhesive" or "prime structural adhesive" are widely used for adhesives which can reliably carry applied loads or stresses like other structural materials. Structural adhesives are generally soft when applied and develop their strength by setting. Some basic distinctions between adhesives may be made by categorizing the way they set. The primary setting reactions are as follows:

Cooling of a Thermoplastic - A thermoplastic adhesive is heated for application and then allowed to cool and become hard. The term "hot melt" refers to adhesives which are hot when applied.

Release of a Solvent - An adhesive can harden as its solvent evaporates. The term "solids" refers to the materials which remain in the adhesive when the "solvents" are removed. An "100% solids" or "100% reactive" adhesive means that no substance condenses or evaporates during setting. Generally, lower shrinkage is associated with "100% solids" or "100% reactive" adhesives.

Polymerization in Situ - Polymerization is a chemical reaction in which molecules of a monomer combine to form large molecules. When two or more monomers react, the process is called copolymerization or heteropolymerization. Polymerization reactions are generally categorized as either condensation polymerization or polymerization by addition. Condensation polymerization means that the polymerization

reaction also forms a condensate of water or some other simple substance. Polymerization by addition means that polymerization is induced by the addition of energy or substances called "accelerators" or "catalysts" or "curing agents"; no by-product or condensate is formed. Generally lower shrinkage is associated with polymerization by addition.

Polymerization can be induced by heat, light, ultraviolet radiation, moisture (e.g. sealants such as silicone or butyl rubber or polysulfide), by the exclusion of air (anaerobic adhesives) or other means.

The most important structural adhesives set by polymerization in situ and the products formed are generally "thermoset"; i.e. the reaction is irreversible and the product is substantially insoluble. Many structural adhesive formulations include "fillers" or substances added to affect specific properties in desired ways. Ductility, permeability, diffusivity, shear strength, adhesion, workability may all be modified by the addition of "fillers". Many formulations are "modified", "alloyed", "hybrid" or "two polymer" adhesives in which two or more primary monomer groups are combined. For example, epoxy-nylon, neoprene-phenolic, epoxy-phenolic, are common "alloyed" adhesive formulations. In many cases the exact composition of adhesives may not be revealed by a manufacturer. Therefore the performance of products nominally called epoxies or acrylics or some other generic name can vary widely. The following are the most important classes of structural adhesives:

Epoxies, Filled Epoxies, Alloyed or Hybrid Epoxies - Epoxy adhesives consist of a resin containing the epoxide group (a specific arrangement of carbon and oxygen atoms) and a curing agent which induces polymerization. Epoxy resins are thermosetting. Properties of epoxy adhesives vary, primarily as a function of:

i) process for preparation of epoxy resin

ii) curing agent

iii) curing temperature and pressure

The most common epoxies used for adhesives are derived from Bisphenol A and Epichlorohydrin ("Bis-Epi" resins) and are usually cured with reactive hardeners containing polyamine groups. The primary alloyed epoxies are epoxy-nitrile rubber ; epoxy-nylon and epoxy-phenolic. Epoxy-nitrile rubber adhesives are characterized by high toughness; epoxy-phenolics by high strength at elevated temperatures (they usually require high temperature cures) and nylon-epoxies by high shear strength and "peel " strength.

Acrylic or "Modified" Acrylic Adhesives - The technology of modified acrylic adhesives is newer than that of epoxies. Ref. [88] states that they were "introduced in the U.S. by Hughson Chemicals" in about 1968. One published description of such adhesives is that they are resins consisting of "polyacrylate monomers and polymers grafted with reactive elastomers" and the accelerator is a "free radical source designed to initiate the free radical polymerization" of the resin. The primary characteristics of such adhesives is that they are well suited for metal to metal bonding; they require less surface preparation; they cure at room temperature on the order of minutes and their performance is comparable with state-of-the-art epoxy formulations.

Other adhesives have also been used for structural bonding, notably anaerobic adhesives, nitrile rubber-phenolics, cyanoacrylate adhesives and polyurethane adhesives. As noted previously, anaerobic adhesives cure when air is removed, therefore they are used primarily for sealing and locking threaded assemblies, for gaskets and as fillers between press fitted parts. Products such as Eastman 910, 3M Scotch Weld CA adhesives and other "wonder bonds" are cyanoacrylate adhesives. Normal recommended "dosage" of such adhesives is one drop per square inch. Cyanoacrylates have minimal void and gap filling capabilities and therefore require very close fitting parts. Polyurethane adhesives generally have lower elastic moduli and lower strengths at elevated temperatures (180^{o}F) than state-of-the-art epoxy or modified acrylic adhesives.

To determine the types of adhesive products currently produced which may be suitable for use on steel bridges, a request for information was mailed to manufacturers. The letter and the list of manufacturers are given in the Appendix. Responses and/or information were received from 19 manufacturers.

One manufacturer, Goodyear, sent information on their structural polyurethane series of adhesives called Pliogrip. Another firm, Devcon, also markets a urethane product (Flexane) which can be cast. Three companies provided data on structural acrylic adhesives: Loctite-Depend 330, Conap-Conastic 830, and Lord Corporation Versilok 201/204. Almost all manufacturers sent information on epoxy structural adhesives. One firm, Polymer Research Corporation of America, proposed formulating a suitable adhesive using proprietary "chemical grafting" technology. The firm stated that their techniques produce much higher bond strengths and, significantly,

that the bonds are not affected by water or weathering.

In general, available adhesive products were formulated to satisfy primarily aerospace or industrial (electrical and mechanical manufacturing and assembly) needs. Ciba-Geigy,Delta Plastics and Adhesive Engineering provide a broad range of products devoted to concrete construction. Manufacturers do provide detailed information on the bonding process. Specifically, procedures for the following steps are given:

1. Surface Preparation - In general, surfaces are prepared by chemical cleaning, abrasion and degreasing. Chemical cleaning means acid etching or acid anodizing. Priming is sometimes recommended to protect a cleaned surface. <u>For bonding steel with epoxy, grit blasting followed by degreasing (e.g. with trichloroethane) is the usually recommended procedure</u>. Alternatively, acid etching may be done. For example, Dexter-Hysol specifies the following steps:

a) Degrease by washing metal in trichloroethane

b) Immerse for 3 to 10 minutes at 75°F in a bath composed of

   1 part by weight of distilled water
   1 part by weight concentrated hydrochloric acid

c) Rinse thoroughly in running distilled or deionized (cold) water

d) Oven dry at 150°F for about 10 minutes

More sophisticated surface preparation techniques have been developed by aerospace companies primarily for aluminum to aluminum bonding. For example, Boeing has developed the "phosphoric acid anodizing" process [31].

For bonding steel with modified acrylic adhesives, surface preparation is less critical. For example, Lord Corp. states that the Versilok 201/204

modified acrylic adhesives can be used with "little or no surface preparation". Of course bond strengths are generally greater if the surface is prepared.

2. Bondline Thickness Control - A lower bound for effective bond thicknesses usually said to be 0.0005"-0.001"; an upper bound is usually 0.010" - 0.015". Adhesive bonds outside those limits will, in general, have lower strength values. For paste adhesives, appropriately sized beads or wires embedded in the bondline provide thickness control. Some adhesives are manufactured as "supported films"; the thickness of the adhesive film or sheet provides an efficient way to attain a uniform bondline thickness, although the gap filling ability of the adhesive is decreased.

3. Adhesive Application - Adhesives are normally two-component formulations which must be mixed in a specified ratio and then spread over the surfaces to be bonded. It is also common to have activator or accelerator substances which are sprayed, rolled or brushed on one or both of the adherend surfaces. The latter is the method usually used for supported film adhesives and modified acrylic adhesives.

4. Curing Temperature and Pressure - Epoxies can cure at a spectrum of temperatures, pressures and times depending on the exact composition of the resin and accelerator. Normally, epoxies require days of room temperature curing to reach full strength. Modified acrylic adhesives, on the other hand, attain a large fraction of their strength in a few minutes of room temperature curing.

5. User Safety and Cleanup - Adhesives can irritate skin and eyes; some are flammable and some release harmful vapors. All user safety recommentations should be followed strictly.

Data received from manufacturers on mechanical properties of structural adhesives is fragmented and primarily for comparative value. Strength properties are often not given for steel to steel bonds and for temperature extremes. Much strength data is obtained using single lap type specimens [89] or peel [90] specimens. Since the stress conditions in such tests are not "pure" (see Chapter V) the data does not provide a clear basis for estimating the strength of bonds having different geometries.

In summary, the information received from manufacturers indicated the following:

1) The primary available structural adhesives are epoxy and modified acrylic formulations
2) The composition of most adhesives products is not revealed by manufacturers
3) Formulations are primarily for industrial/aerospace needs; adhesives for civil engineering/construction applications are primarily for concrete
4) For bonding steel, surface abrasion by grit blasting followed by degreasing is the recommended surface preparation
5) Only sparse data on mechanical properties is provided by manufacturers; what data exists has primarily a comparative rather than a predictive value

In light of such observations, it is probable that some experimental evaluation will be required for any candidate adhesive before it can be used on bridges. Moreover, the exact form of the tests remains to be developed. Chapters IV and V address the theoretical and experimental problems associated with the engineering description of adhesives.

CHAPTER IV

CONSTITUTIVE EQUATIONS, STRENGTH AND BOND BEHAVIOR

Introduction - The primary way of describing structural materials in an engineering sense is by stress-strain or constitutive equations and a strength theory. For example, in structural analysis and design, steel is often assumed to be a homogeneous, isotropic, linear elastic or elasto-plastic material. The strength of steel in the majority of applications is computed from data obtained in uniaxial tensile tests. This chapter reviews the meaning of several basic forms of constitutive equations to determine if they are suitable for modeling adhesives. Similarly, several theories for predicting the strength of structural adhesives (i.e. the cohesive strength) and the adhesion strength are discussed. In addition, several processes which can affect the stress-strain and strength properties of bonds are noted.

Constitutive Equations - A variety of constitutive relations have been proposed for the spectrum of engineering materials; it is impossible to enumerate them all. In order to review elements of material behavior, only four basic constitutive forms will be discussed. They are represented in terms of one-dimensional elements in Fig. 4.1 . The linear elastic model, shown in Fig. 4.1a is the most widely used and most easily understood constitutive relation. Strain is linearly proportional to stress; if one quantity is held constant, there is also no time variation in the other. Fig. 4.1b shows three of the many possible linear, viscoelastic constitutive models. Two aspects of material behavior which can be modeled by linear viscoelasticity are creep and relaxation. To explain these terms, the behavior of the "standard linear solid" is depicted in Fig. 4.2 . Fig. 4.2a shows the behavior of the model

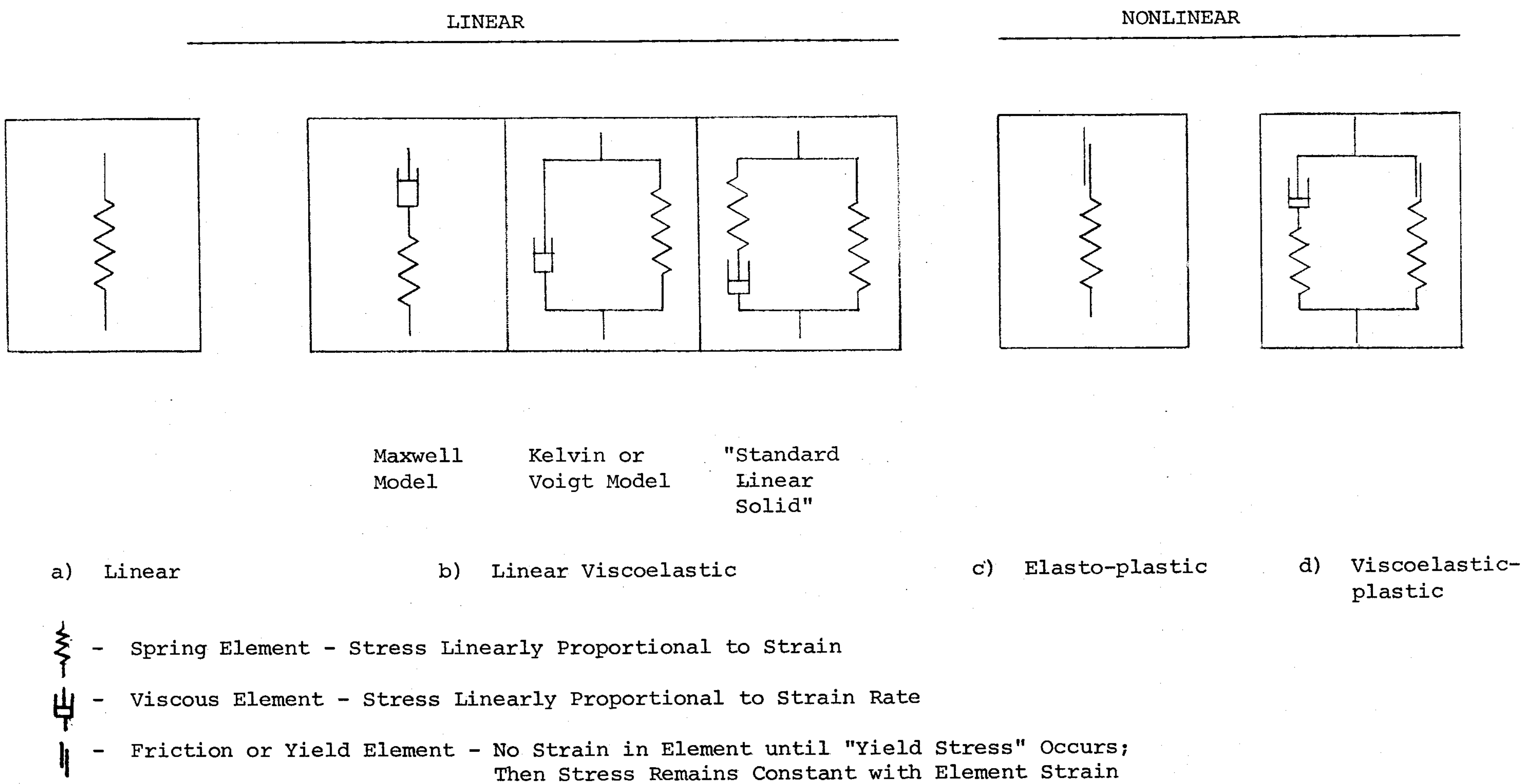


Fig. 4.1 Four Common Constitutive Models

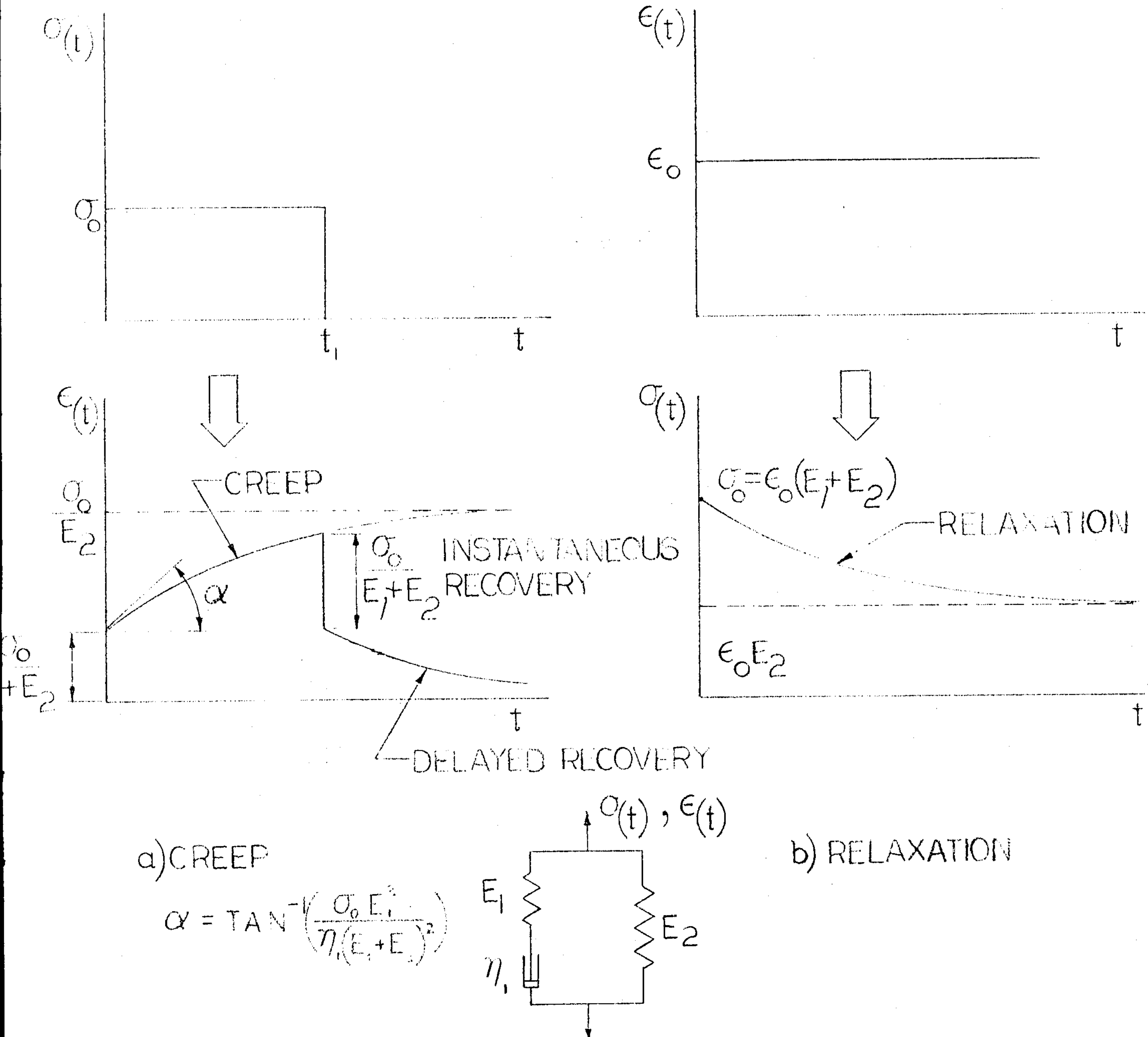


FIG. 4.2 BEHAVIOR OF A THREE PARAMETER LINEAR VISCOELASTIC MODEL

subjected to a constant applied stress. As the stress is applied there is an instantaneous strain then, in time, additional "creep" strain occurs. When the stress is removed, there is an instantaneous decrease in strain and then, in time, a delayed recovery. If a fixed strain or deformation is applied, there is an instantaneous stress which decreases or "relaxes" in time to a lower value. The latter behavior is shown in Fig. 4.2b.

Fig. 4.1c shows the common nonlinear, elasto-plastic model often used for steel. It can represent yield phenomena but not creep or relaxation. It is non-linear because the stress-strain relationship is a function of the magnitude of the strain. The model shown in Fig. 4.1d combines elements of viscoelasticity and plasticity; it can represent yielding, creep and relaxation.

Published studies on the behavior of structural adhesives can provide guidance on the suitability of alternate constitutive forms for adhesives. Because of the variety of structural adhesives available, it is not uncommon to find that "X" studies used "X" completely different materials. It is also understandable that properties vary considerably so that generalizations or "ballpark" numbers have limited usefulness. Therefore the following observations on adhesive behavior are given primarily to identify areas of potential concern.

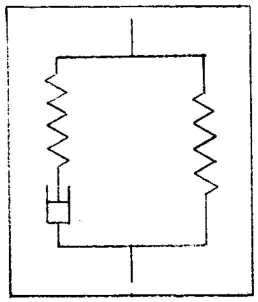
Structural adhesives are, in general, assumed to be homogeneous and isotropic. They exhibit linear elastic behavior only at very small stress levels (unless the adhesive is in a hydrostatic stress state). Adhesive stress-strain curves are sensitive to the rate of loading or deformation. Creep and relaxation phenomena occur at a broad range of stress values. Renton [65], Sancaktar and Brinson [20], Hughes and Rutherford [56] and many others have studied creep in adhesives. Creep increases as temperature

and relative humidity increase. Creep behavior of adhesives in shear differs from that of adhesives in tension [65][20][56]. Creep strains are found to be larger in the shear mode. Adhesives exhibit plastic flow; the exact "yield stress" level may be dependent on the strain rate. Delayed failures or creep ruptures do occur in adhesives subjected to a constant load (see also Chapter V).

The above observations indicate that time dependent effects are important in adhesives. Therefore constitutive models which have some viscoelastic elements may be most suitable for adhesives. Fig. 4.3 shows a sample of constitutive models which have been used by several investigators (of course linear elastic models have also been used).

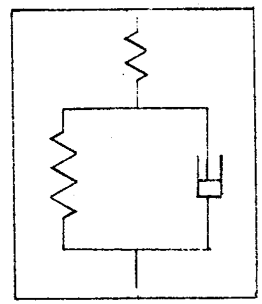
Bond Strength - Adhesive constitutive equations are used for predicting the stress strain behavior of adhesive joints. Stress fields under given loading conditions as well as time variation of stresses and strains can be studied. For engineering design, the strength of the bond is most important and engineers must estimate which stress or strain conditions may lead to bond failure. As noted in Chapter II , bond failure can either be an adhesion failure at the interface between the adhesive and the adherend or a cohesive failure within the adhesive material. These two failure mechanisms must, in general, be studied for different static stress conditions, for fatigue loads, for design environmental conditions and for sensitivity to flaws or stress concentrations.

Cohesive strength (of adhesive material) - One of the consequences of thin bondlines and of the fact that steel adherends are much stiffer than polymer adhesives is that adhesives in bonded joints are usually in a three-dimensional stress state (a detailed explanation is given in Chapter V).



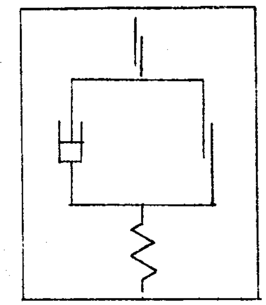
a) Linear Viscoelastic

Renton [65]



b) Linear Viscoelastic

Dalale and Erdogan [75]
Romanko and Jones [36]



c) Viscoelastic-Plastic

Sancaktar and
Brinson [20]

Fig. 4.3 Some Constitutive Models used for Structural Adhesives

An implication of this is that strength data from uniaxial tensile tests of bulk adhesive specimens is insufficient for predicting the strength of adhesives in actual use conditions. Therefore to estimate strength either the exact bond configuration must be tested or a theory which predicts strength in various stress conditions from fundamental uniaxial strength data must be known. The impracticality of the first alternative emphasizes the need for a workable method to estimate adhesive strength. Common strength theories are presented in numerous texts [91],[92]; the theories propose that failure occurs when a critical value of a specified response is reached. Some of the responses used are normal stress or strain, shear stress (the Tresca criterion) or strain, total elastic strain energy and elastic <u>distortional</u> strain energy (the Von Mises criterion). The distinction between the latter two criteria is very important. Total elastic strain energy may be divided into a component arising from volume changes associated with a hydrostatic stress state and a component arising from distortion of a volume. Thus when elastic distortional strain energy is used as a failure criterion, the inherent assumption is that strength is not a function of the magnitude of the hydrostatic stresses which implies that a material in a hydrostatic stress state does not fail. Many metals obey a yield criterion which is independent of hydrostatic pressure.

Adams and Coppendale [61] point out that the yield stress of many polymers has been found to depend on the hydrostatic stresses. Therefore several modifications of the Tresca and Von Mises criteria have been proposed for polymers. One used is the Coulomb-Mohr criterion (used in soil mechanics) which states that yielding occurs when the shear stress on any plane reaches a critical value which varies linearly with the stress normal to that plane. Ikegami et al. [42] have published excellent experimental data which tend

to corroborate the Coulomb-Mohr criterion. Fig. 5.8, from Ikegami [42], shows failure data for bonded steel specimens subjected to combined shear and normal stresses; the failure locus may be estimated as a straight line, which is in agreement with the Coulomb-Mohr criterion. Adams and Coppendale[61] also discuss several other criteria in which the shear stress causing yield increases linearly with the hydrostatic pressure. They note that:

> ". . if a pressure dependent yield criterion is applicable, a substantial difference between butt joint tensile and compressive yield stress can be expected for typical values of adhesive Poisson ratio. . . . .It should be noted that the yield stress of butt joints in compression is very sensitive to small changes in Poisson's ratio in the range 0.35 to 0.4 which are typical values for structural adhesives. . . . If the Poisson's ratio exceeds a certain value...the butt joint will never even begin to yield under the influence of a compressive load."

Adams and Coppendale report tests on butt joint specimens loaded in compression up to 340 MPa (49 ksi). Up to that stress the stress strain curves were linear; no apparent yielding occurred.

Many bonds are subjected to cyclic loads so the fatigue strength of adhesives must also be known. Jablonski[1], Romanko and Jones [36], Krieger [29] and others have investigated the parameters which control adhesive fatigue life. Most studies are experimental, using small scale specimens. Large scale fatigue tests similar to those reported in Chapter II are not common.

The fracture toughness and the flaw sensitivity of the strength of an adhesive may also be important design concerns. Sih [13], Hunston et al. [14], and others have applied fracture mechanics principles to adhesive bonds.

In brief, there are many aspects of the strength of adhesive materials; one or several may be important for a specific application. Because of the relative newness of structural adhesives, their variety, the viscous aspects

of their behavior and the three-dimensional stress states in which they operate, much work remains to be done on quantifying their strength.

Adhesion - No generally accepted theory exists which explains adhesion phenomena and adhesion strength. For metal to metal bonding with polymer adhesives, it is generally believed that the primary bonding phenomena are attractive forces at the molecular level. Bonding by chemical reaction between the adherend and the adhesive generally does not occur (see however pg.43 for capabilities of Polymer Research Corp.) in metal-polymer-metal bonds. Similarly, mechanical interlocking between materials is not considered to be the primary adhesion mechanism, except for porous adherends such as wood or paper. Abrasion of the adherend may, however, increase the strength of the bond under certain loading conditions. Abrasion cleans a surface, removes weak films or oxide layers, increases the surface area by adding roughness and hence may increase mechanical interlocking. Good adhesion requires clean adherend surfaces and adhesives which can "wet" the surface, i.e. come into close and "complete" contact with the adherend without leaving many voids.

Regarding the relative strength of adhesion vs. the strength of adhesives, Zisman in Ref. [78] p. 54 states:

> "When conditions of complete wetting and freedom from the formation of gas pockets and occlusions prevail, the adhesion to either high-energy or low-energy surfaces will usually be ample, and generally failures of the joint will be in cohesion."

but:

> "Because of the existence of pores and cracks in the surfaces of real solids, surface occlusions or gas pockets will always be formed to some extent on applying the adhesive. The resulting loss in joint strength can be large . . ."

Further

> "There has been much discussion about the necessity for using

adhesives capable of forming chemical bonds with the adherends. But . . . considerations concerning the relation of wetting to adhesion have made it evident that the energy involved in the physical adsorption to the adherend of molecules of adhesive is more than sufficient to form joints which are stronger than the solidified bulk adhesive. Of course chemical bonding may be desirable to obtain greater heat, water or chemical resistance rather than any needed increase in the specific adhesion"

Therefore adhesion strength is usually considered to be the stronger link when a bond is made. However it may become the weaker link as processes which degrade the adhesion occur in time. Some of those processes are discussed in the following section.

Aging of Bonds - A joint must be durable in design stress and environmental conditions. Therefore any process which affects strength or other properties of bonds should be understood and controlled. A major problem which has retarded the use of adhesives in structural applications has been the adverse effect moisture may have upon the bond strength. Therefore the parameters which control the diffusion of water in the adhesives as well as the effects of the process have been studied extensively. Important results of such studies are as follows:

Diffusion of water in bulk epoxy - Epoxides are moderately hydrophilic, with a diffusion coefficient on the order of 10^{-13} m^2/sec at a temperature of $25^{o}c$. The main parameters which control the diffusion of water are the diffusivity of the material, relative humidity and temperature. In general, diffusion increases as the parameters increase; Morgan and Mones [51] and Brewis et al[2] quantify the increases. Absorption of water causes a weight gain in epoxies of about 1% to 5% at equilibrium conditions. Mechanical properties are also affected. Tensile strength and Young's modulus of an epoxy which has absorbed water are smaller than those of a dry sample.

The rate of diffusion of water has been predicted well by Fick's law of diffusion [64]. However, Morgan and Mones [51] note that any damage induced in an epoxy by applied stress, fabrication or environmental conditions can accelerate moisture diffusion beyond rates predicted by Fick's law. For example, they give experimental evidence which shows that application of axial stresses above 38-40 MPa (5.6 ksi) for a period of one hour increases the amount of water absorbed by an epoxy at equilibrium by about 11% above that of an unstressed specimen.

Water diffusion in bondlines - Brewis, Comyn, Maloney and Tegg [2] by very careful measurements on unstressed bonds noted that:

> "Transport of water into adhesive joints is certainly no faster than can be accounted for by diffusive transport; thus in the systems studied, there is no evidence of water transport along the adhesive-substrate or adhesive-carrier interface."

For stressed bonds, such a conclusion may not be valid, and all three mechanisms noted may contribute to the ingress of water. Moisture migration in the bondline decreases the bond strength and changes the character of the failure from primarily cohesive to primarily adhesion. Both the properties of the adhesive and the surface of the adherend are degraded by diffusion of water. Fig. 4.4 from Ref. [4], indicates the decrease in bond strength for double lap aluminum specimens exposed to warm, moist air (50°c and 100% R.H.). Ref. [4] also denotes that the failure mode for exposure times over 5000 hrs. is increasingly interfacial or an adhesion type. A variety of mechanisms have been proposed for this water-induced strength loss. Cherry and Thomson [15] note that for epoxy-aluminum bonds:

> "The proposed mechanisms include the thermo dynamic instability of the epoxy-aluminum interface in the presence of water, the disruption of the polymer-polymer bonds, hydration of the oxide layer, or corrosion and preferential absorption of water to the oxide, displacing the adhesive."

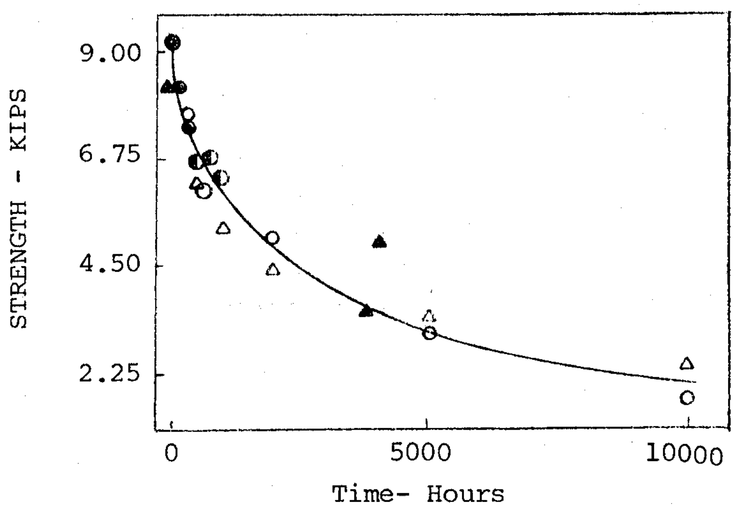


Fig. 4.4 (from Ref. [4]) Dependence of joint strength on exposure time for double lap joints with chromic acid etched adherends. Circles and triangles denote two different adhesives. Open symbols mean unstressed joints; filled symbols mean joints stressed to 20% of dry strength

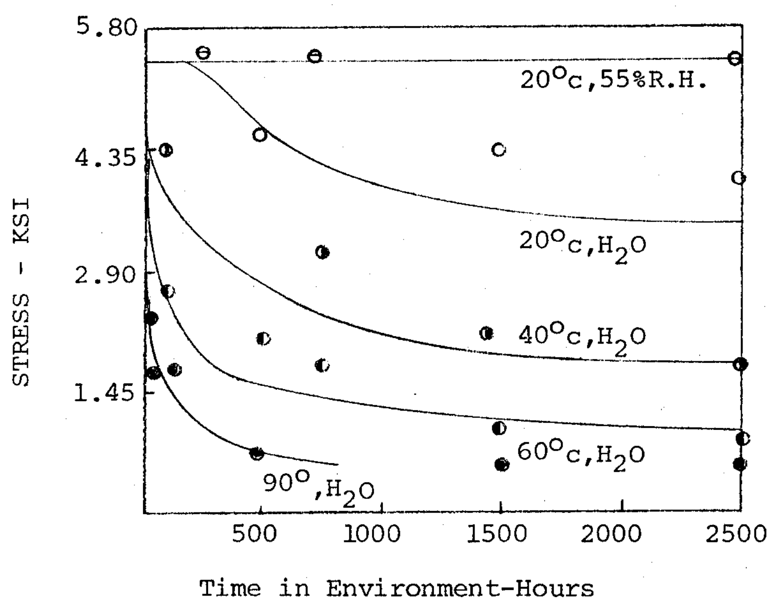


Fig. 4.5 (From Ref. [43]) Butt joint fracture stress versus time in environment. Points are experimental measurements and solid curves are theoretical predictions.

Brewis et al [2] note that the "hydration of the oxide layer" mechanism:

> ". . . accounts for the observed incomplete recovery of strength of [sic] drying, since water removed would result in a cracked oxide."

Andrews and Stevenson [16] report similar strength losses for titanium-epoxy bonds in aqueous environments. They further show experimentally that acidic or low pH water produces the most rapid decrease in bond strengths.

Several methods for improving durability have been suggested. Clearly, development of an adhesive with a much smaller diffusion coefficient could decrease or eliminate the problem. To meet present needs aerospace firms have developed (for aluminum and titanium adherends) phosphoric or chromic acid anodizing processes which produce durable oxide layers. But such methods may be effective only for limited exposures (to about 5000 hrs [4]). Hertz [25] reports that moisture barriers have been used. One consists of multilayers of thin aluminum foil bonded to structures using overlapping joints; another is "a tin-indium eutectic coating (Patent No. 4,022,585) over a thin copper coating"[25].

Bond durability remains an important issue. For bridge applications, the large bonded areas may be beneficial in controlling degradation. Nonetheless, it is likely that a way of predicting long term strength or durability will be required. Gledhill, Kinlich and Shaw [43] have, in fact, proposed such a method for tensile butt joints using mild steel adherends and epoxy adhesives. Fig.4.5, from Ref. [43] shows their prediction vs. observed data for specimens immersed in water up to 2500 hrs.

Summary - This chapter has briefly reviewed the state-of-the-art in constitutive modeling of adhesive materials in estimating short term strength of adhesives and adhesion in bonds and in understanding processes which effect bond durability. The primary observations made are as follows. Linear elastic constitutive models may be inadequate for predicting important stress-strain behavior of adhesive joints. The relatively complicated stress state in which adhesives work means that data from one-dimensional tests of bulk adhesives may be inadequate for predicting adhesive strength so an appropriate strength theory may have to be used. Adhesive and adhesion strengths may degrade with time; one important process which affects the degradation is the diffusion of water in the bond. Prediction and control of long term degradation remain important design concerns.

CHAPTER V

Engineering Properties of Bonds

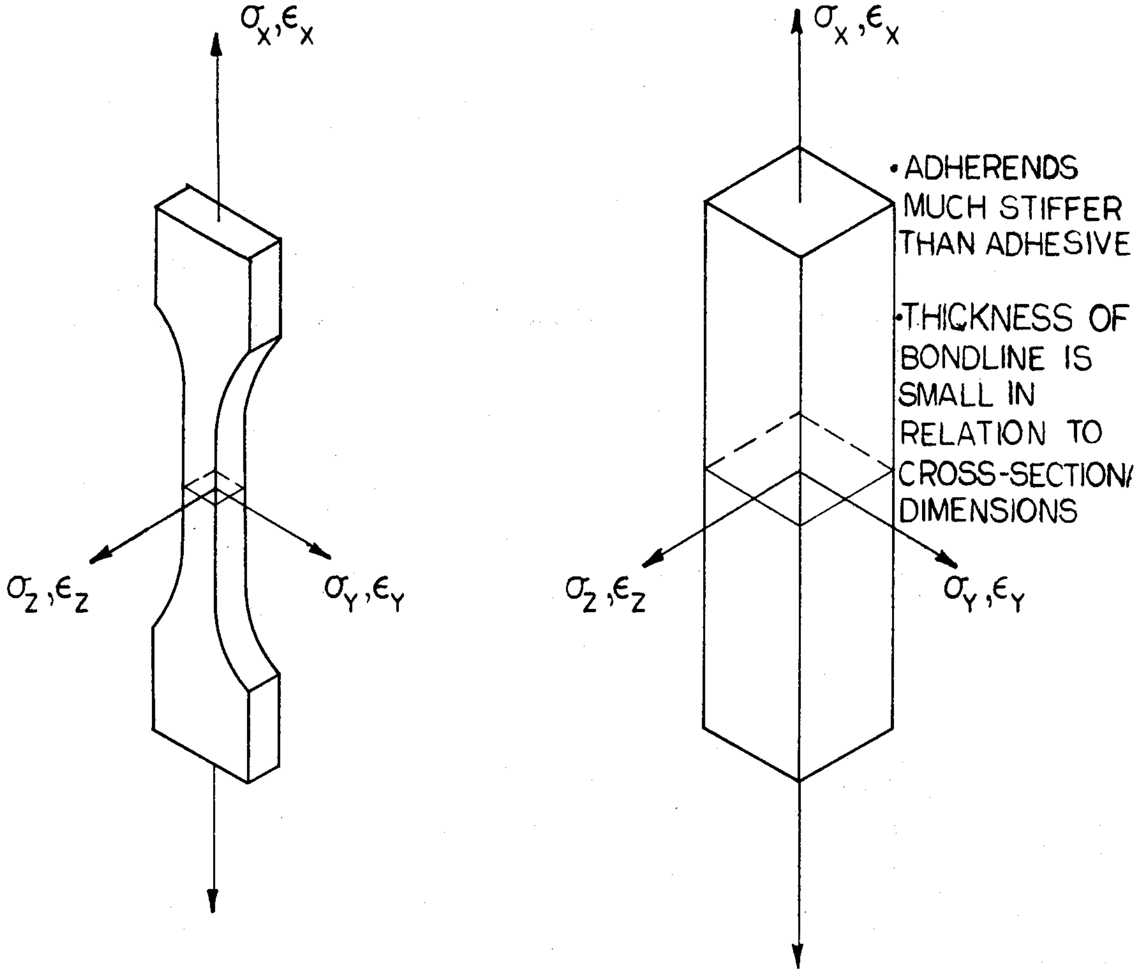
Engineering properties of adhesive bonds are required for analysis and design of bonded connections. This chapter reviews and evaluates experimental methods used to obtain adhesive stress-strain properties and bond strengths. Common tensile and shear tests are analyzed in detail and some other bond geometries are discussed.

The preliminary work performed to identify adhesives suitable for study is presented. Experimental studies on measuring adhesive strains, on obtaining elastic moduli, on strength of bonds in pure bending and on creep rupture are reported.

Tensile Tests - Since tensile tests of common structural materials conventionally use bulk specimens, it is instructive to contrast the behavior of bulk adhesive tensile specimens with the behavior of tensile adhesive "butt joints". Fig. 5.1a shows a typical bulk tensile specimen. As an axial load is applied, the specimen is placed in an uniaxial stress state; however, normal strains occur in all three directions. If the axial strain, ε_x, is measured, then the modulus of elasticity is simply calculated from:

$$E = \frac{\sigma_x}{\varepsilon_x}$$

The specimen fails when the applied stress reaches the material's uniaxial strength.



A) BULK ADHESIVE SPECIMEN

$\sigma_Z = \sigma_Y = 0.0$
$\epsilon_Y \neq 0$
$\epsilon_Z \neq 0$

B) BUTT SPECIMEN

$$\left.\begin{array}{l}\sigma_Z \neq 0.0 \\ \sigma_Y \neq 0.0 \\ \epsilon_Z = \epsilon_Y = 0.0\end{array}\right\} \text{FOR MOST OF BONDED AREA}$$

FIG. 5.1 BULK VS. BUTT TENSILE ADHESIVE SPECIMENS

The behavior of the adhesive in a butt joint as shown in Fig.5.1b is quite different. Adhesives have a much lower modulus of elasticity than steel ($E_{steel} \simeq 30 \times 10^6$psi; $E_{adhesive} \simeq .5 \times 10^6$psi) and the nominal dimension of the cross-section of a butt joint is much larger than the bondline thickness. As a result, when an axial load is applied to a butt joint, the stiff adherends restrain the ε_y and ε_z (see Fig.5.1b) strains in the adhesive over a large portion of the bonded area. Therefore stresses in those directions occur and the adhesive is in a triaxial stress state. If ε_y and ε_z are set to zero, then the elasticity relation between σ_x and ε_x is:

$$\sigma_x = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \varepsilon_x = E^* \varepsilon_x \tag{5.1}$$

in which ν is Poisson's ratio. In effect the adhesive elongates with an apparent modulus E*. Poisson's ratio is commonly between 0.35 and 0.40 for adhesives therefore E* is between 1.60 E and 2.14E. An excellent discription of the stresses in a butt joint is given by Adams and Coppendale [61]. Fig.5.1c adapted from Ref. [61], shows qualitatively how stresses vary in the (circular) cross section of a butt joint. In the central region of the joint the axial stress is uniform and there are no shear stresses. The radial and circumferential stresses, which arise from the restraint of the corresponding strains, are also constant in the middle region and approximately equal to each other. On the periphery of the joint the longitudinal stresses decrease and some shear stresses occur. Adams and Coppendale [61] state:

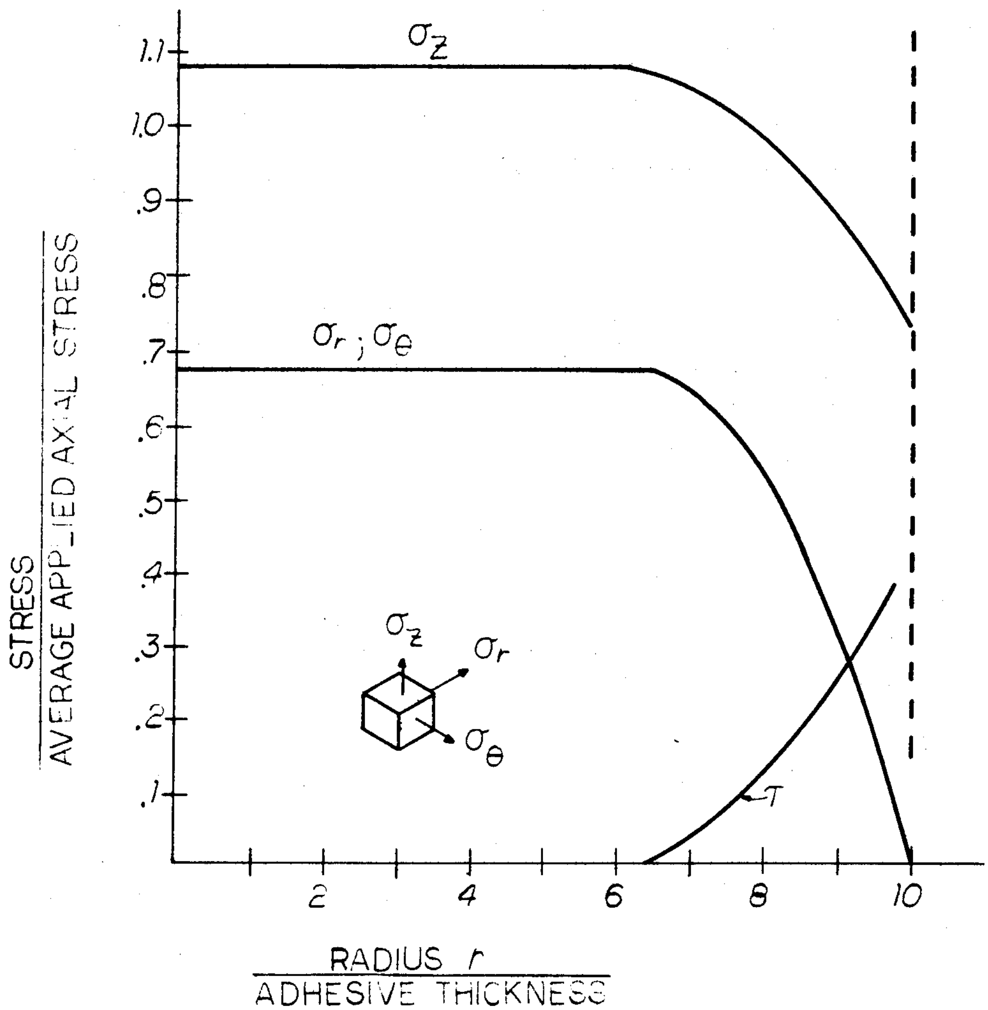


FIG. 5.1c (ADAPTED FROM REF. [61])
QUALITATIVE STRESS DISTRIBUTIONS
RATIO OF SPECIMEN DIAMETER TO
BONDLINE THICKNESS IS 20; $\nu_{ADHESIVE} = 0.4$

"For a particular value of adhesive Poisson's ratio, the radial width of the peripheral region (measured in terms of adhesive thicknesses) is independent of the diameter of the butt joint. For example, if the Poisson's ratio of the adhesive is 0.4, the peripheral region extends inwards approximately three adhesive thicknesses from the outside of the joint. Therefore, in a typical joint with a diameter approximately two orders of magnitude greater than the adhesive thickness, the stresses are uniform over a large proportion of the total bonded area.

Up to the failure load, the axial stress-strain behaviour of the butt joint will depend primarily on the response of the adhesive to the stress state in the central region of the joint, where the σ_r and σ_θ stresses are equal to each other but are less than the applied stress, σ_z. When a tensile load is applied to the joint, the stress state is equivalent to a uniaxial tensile stress, $\sigma_z - \sigma_r$ combined with a negative hydrostatic pressure, σ_r. Similarly, a compressive load applied to a butt joint induces a uniaxial compressive stress superimposed on a positive hydrostatic pressure."

The strength of a butt joint is quite different from that of bulk specimens. First, failure in a butt joint can either be an adhesion failure or a cohesion (i.e. failure in the adhesive) failure. Even assuming that an adhesion failure is precluded, the relation between the strength of butt joints and that of bulk specimens depends on the ductility of the material. In a butt joint the predominantly triaxial stress state in the adhesive causes the adhesive to yield at a stress greater than the uniaxial yield stress. Conversely, the presence of stress concentrations at the periphery can, if the adhesive is brittle, cause a butt joint to fail at a lower stress than a bulk specimen. Such differences make the use of bulk adhesive specimens for obtaining strength values very uncertain.

Ikegami et al [42] and other investigators have used tubular type butt specimens as shown schematically in Fig. 5.2<u>c</u>. In such

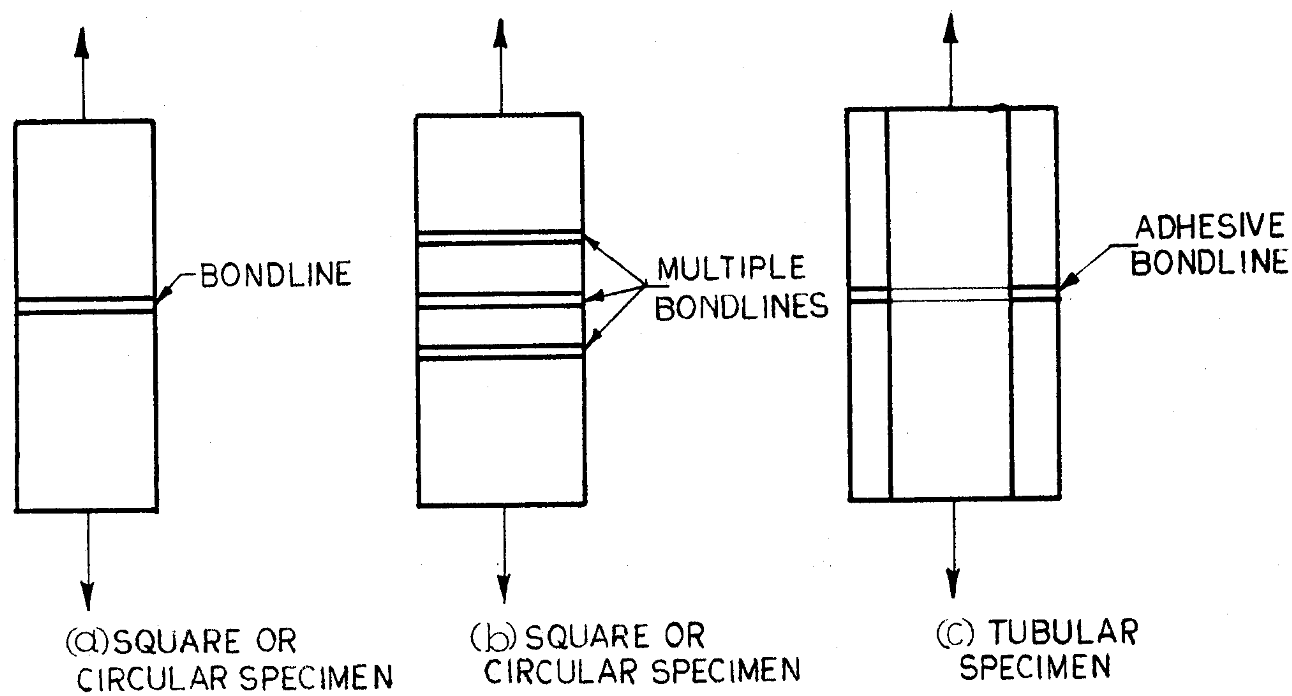


FIG. 5.2 ALTERNATE ADHESIVE BUTT JOINT
SPECIMENS

specimens, if the thickness of the tube wall is not much greater than the thickness of the bondline, the assumption that ε_z is zero is less valid. Therefore the adhesive behaves with a different apparent modulus than in butt joints with large, solid cross sections. A distinct advantage of tubular specimens is that the same specimen can be tested in shear (by applying a torque) and in combined shear/axial stresses.

In all tensile tests, the measurement of strain in the adhesive is a significant problem. Perhaps the best available method is that of Rutherford and Hughes [56] who have developed a capacitance type extensometer. Adhesive strain causes the gap between two plates to change its dimension and hence its capacitance. The reported sensitivity is 2×10^{-6} inches. It has been used to study creep in adhesive joints. Another extensometer for bonds has been developed by Krieger [29]. The technique used by Adams and Coppendale is to use a series of bondlines as shown in Fig. 5.2b. The intended effect is to increase the total elongation. A conventional extensometer (they used a 1" gauge length) then has sufficient sensivitity. Of course the extensometer data must be processed to account for the multiple layers and the (small) strains in the metal adherend.

A technique tried in our research was to bond strain gauges directly across bondlines. Then, if L is the gauge length and t is the bondline thickness, the strain in the adhesive was computed from:

$$(\varepsilon_{adhesive})(t) + \varepsilon_{steel}(L-t) = (\varepsilon_{gauge})(L)$$

$$\varepsilon_{adhesive} = \frac{(\varepsilon_{gauge})(L) - \frac{\sigma_{steel}}{E_{steel}}(L-t)}{t} \qquad (5.2)$$

It was assumed the E_s is given and that the stress in the steel was simply the applied load divided by the bond area. The technique is very expensive and the concentration of strain at the bondline causes early gauge failure.

The ASTM D897 standard butt joint specimen is shown in Fig. 5.3 . The specimen is essentially a spool which has been cut in half at a plane normal to the longitudinal axis of the spool. The spool halves are bonded together to form the original shape and loaded with an axial load perpendicular to the bonded plane at a rate of 1200-1400 psi/minute nominal stress on the bonded area. The load is applied through a fixture shown in Fig. 5.3 . Each half of the fixture may be described as a "c" shaped cavity which receives the rim or flange of the spool so that a tension force can be applied. Only about 72% of the available rim area of the spool is loaded because of the "c" design of the fixture. Therefore it is virtually impossible to apply a concentric load; bending stresses are superposed on nominal tensile stresses. Experiments in which the spool specimens were instrumented with strain gauges have verified that substantial eccentricity occurs. In effect, tensile strength values obtained from ASTM D897 tests are much lower than strength values obtained from experiments with improved load concentricity. Indeed Petronio (p. 96 in Skiest [78]) states:

> "One major difficulty arises with the spool-type tensile specimens. Cleavage is introduced in testing the specimen which results in substantially lower strengths. For example, an adhesive that will demonstrate a tensile strength of 6500 psi when tested in a center and axially loaded specimen...will fail at about 3700 psi using a spool-type specimen even though self-aligning grips are used."

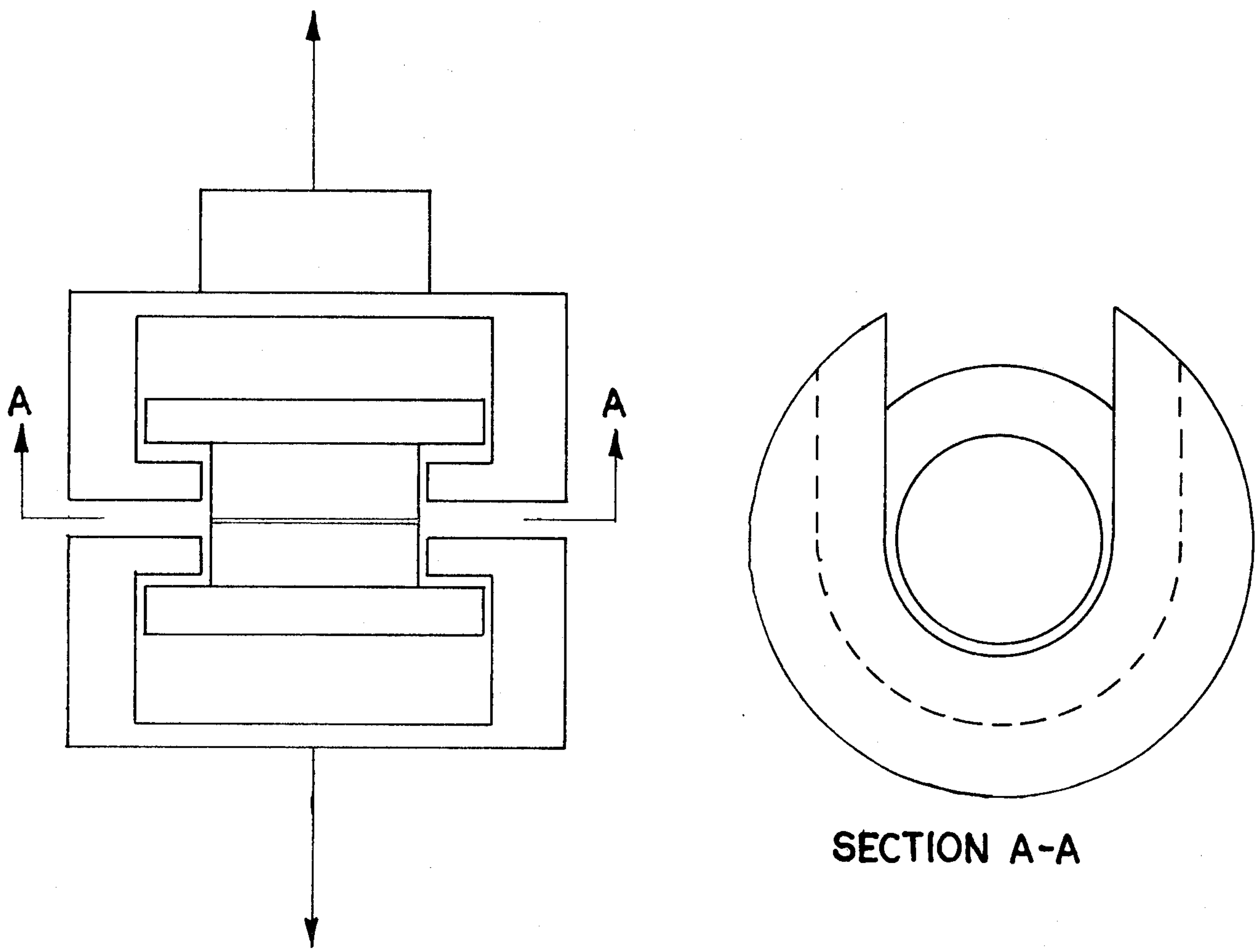


FIG. 5.3 ASTM D 897 TENSILE SPECIMEN

It is the authors' opinion that although the ASTM D897 test may have value in comparing the relative strengths of adhesives, it should not be used as a procedure to obtain absolute ultimate tensile strength data.

Shear Tests - It is generally held that the most effective way to transfer a load by an adhesive bond is to arrange the connection so that the adhesive is primarily in shear. Therefore the most common adhesive bond tests are those which try to measure shear strength. Single lap, double lap, tubular lap and butt joints in torsion are some of the specimen geometries used. It is important to examine the stress distributions in such specimens to try to reconcile the strength data from several different specimens.

1) Single Lap Shear Test. The single lap shear test, ASTM D1002-72, is the most widely used test for obtaining shear strengths of adhesive bonds. The specimen geometry is shown in Fig.5.4a. It should be observed that, because the applied axial loads are offset, the specimen can be in rotational equilibrium only if bending moments are present in the adherends. For a given load, such bending moments are larger for thicker adherends. As the applied axial load is increased, the bending moments increase until the plastic moments of the adherends are reached. Beyond that point, the axial load cannot be increased unless the offset is allowed to decrease. If that is done, the final geometry will be as shown in Fig.5.4c. The implication is that the stress analysis of the joint is a large displacement problem, i.e. the position about

which equilibrium is stated evolves as the load increases. The behavior of such a joint was originally explained by Reissner [6]. Fig.5.4b shows qualitatively the primary results of Reissner.

The largest stresses acting on the adhesive are the shear stresses and the normal "tearing" stresses. They have maximum values near the ends of the lap and decrease toward the line of symmetry. The normal stresses may have absolute values greater than the shear stresses. Increasing the lap distance decreases the tearing stresses. Delale and Erdogan [75] have performed a stress analysis of the single lap joint using viscoelastic constitutive equations for the adhesive. They obtained stress distributions similar to those shown in Fig.5.4b. However, because of the visco-elasticity, they found that the shear and normal stress concentrations near the ends decrease with time.

Of primary importance is the fact that the normal "tearing" stresses affect the strength of the adhesive and of the joint. Thus, strength values obtained from such tests cannot be interpreted as "pure shear" strengths.

2) Double Lap Shear Tests. Segerlind [9], Keer and Chantaramungkorn [11], Yuceoglu and Updike [45] and others have performed linear elastic stress analyses of double lap joints. Lerchenthal [8] has done photoelastic studies of double lap joints having different end details. The studies are all in substaintial agreement.

As in single lap joints, the largest stresses are shear and normal tearing stresses. Fig.5.5 shows the variation of the shear stress along the bondline as the lap length increases. For a very short lap, the shear stress is nearly uniform. As the lap length is increased, the load transfer takes place primarily near the ends, beyond a certain length, further increases do not affect the shear stress distribution. Although not indicated in Fig. 5.5 , the free adhesive boundary at the two ends of the lap implies that the shear at the ends must be zero. Therefore there must be a rapid drop from a maximum value near the end to zero at the end. Fig.5.6(from Refs.[45] and [9]) shows quantitative stress results for particular specimens. The normal stresses are of the same order of magnitude as the shear stresses.

As the adhesive is loaded beyond the elastic range, the stress distributions will change. The ductility of the adhesive will control the relative strengths of short vs long double lap joints. In all cases, the normal stresses contribute to failure of the joint.

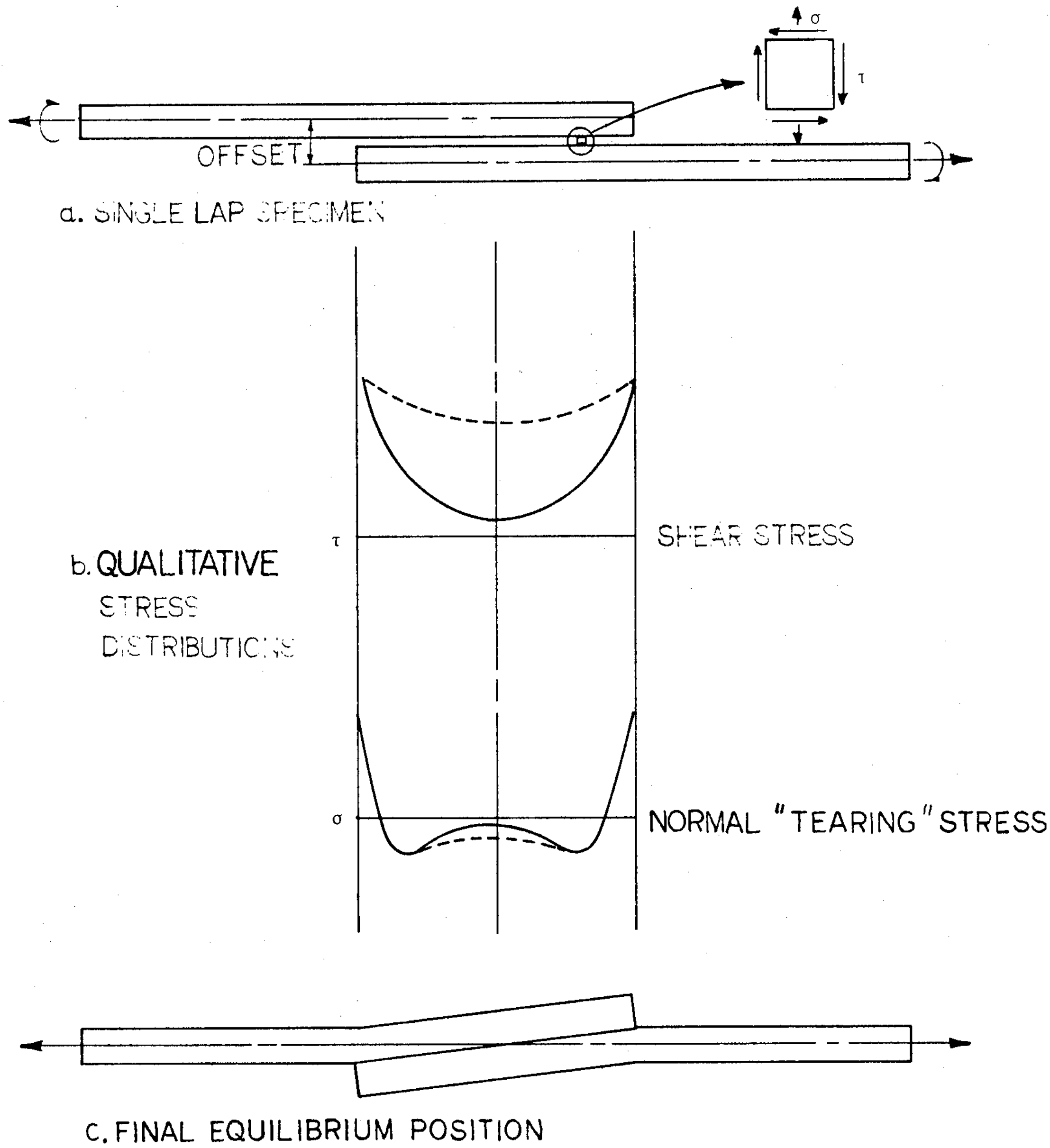


FIG. 5.4 BEHAVIOR OF SINGLE LAP SHEAR SPECIMEN

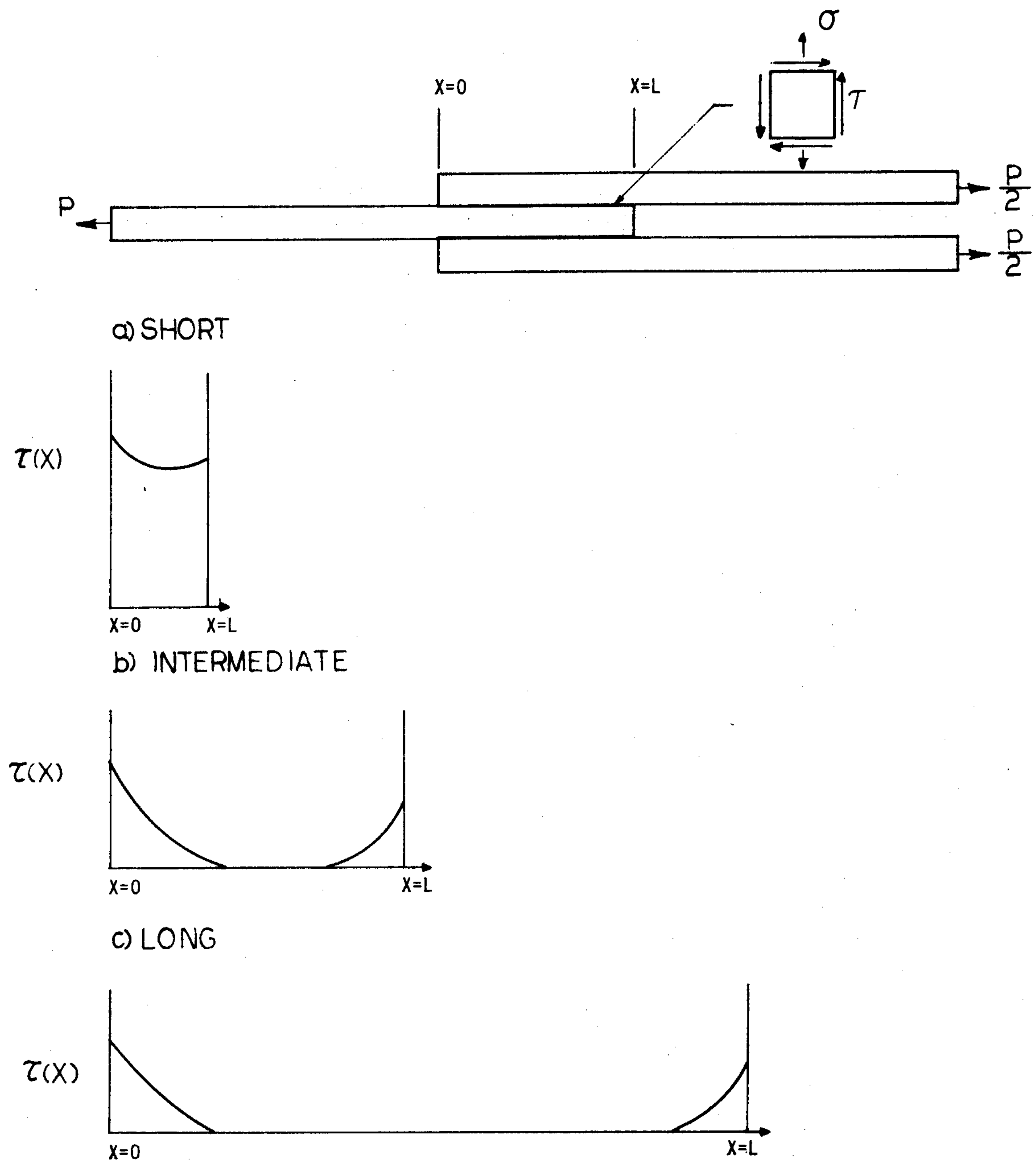
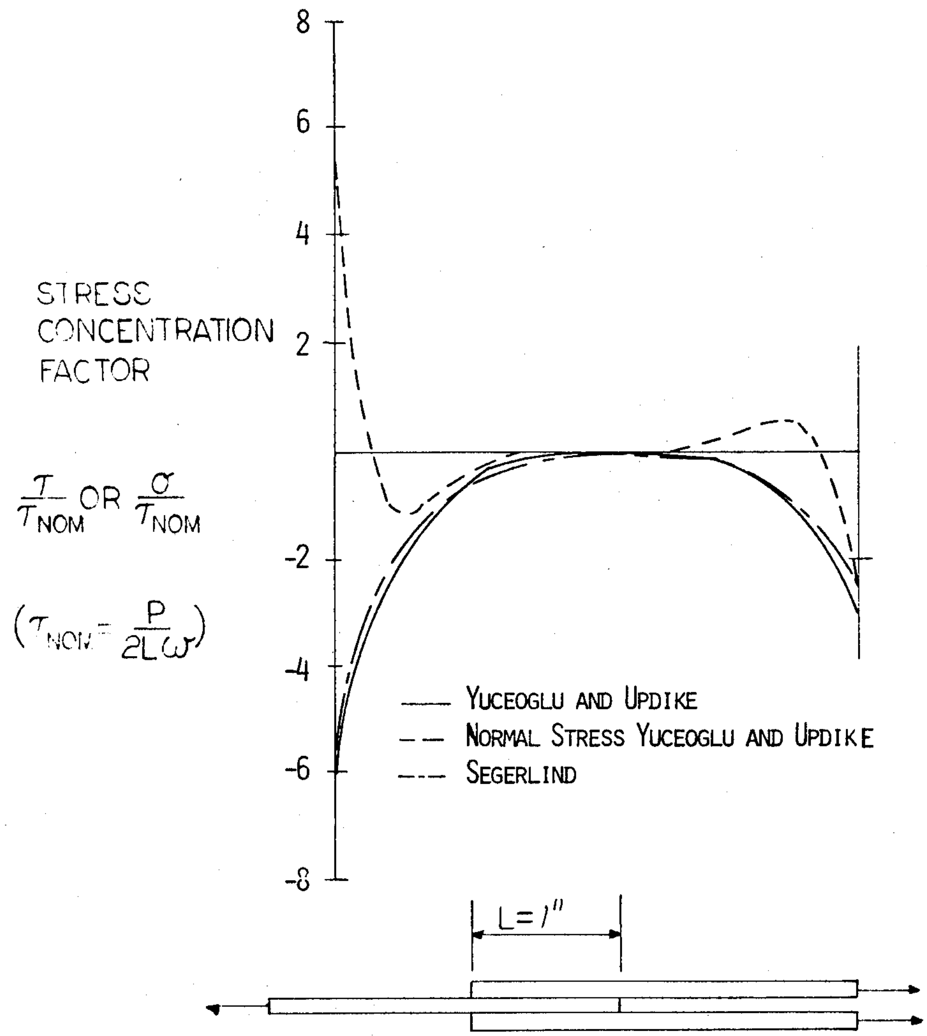


FIG. 5.5 SHEAR STRESS DISTRIBUTION IN DOUBLE LAP JOINTS WITH CONSTANT LOAD AND VARYING LENGTH



1. Al $t=0.09''$; $E=10\times10^6$ psi; $\nu=0.3$
2. BORON-EPOXY COMPOSITE $t=0.03''$ $E_{AXIAL}=32.4\times10^6$ psi
   $G=1.23\times10^6$ psi; $E_{TRANSVERSE}=3.5\times10^6$ psi

ADHESIVE-EPOXY $t=0.004''$ $E=.445\times10^6$ psi; $G=.165\times10^6$ psi

FIG. 5.6 (FROM REFS. [45, 9])
NORMAL AND SHEAR STRESSES IN A DOUBLE LAP JOINT WITH SPECIFIC PROPERTIES

3) Tubular Lap Tests - Adams and Peppiatt [39] and Nagaraja and Alwar [47] present stress analyses of tubular lap specimens subjected to axial loading. Their results are in agreement; they are shown qualitatively in Fig.5.7. Both shear and normal stresses are present as in flat lap joints but the magnitudes of the stress concentrations at the ends are smaller than those found in flat lap joints. The stress distributions are not symmetrical about the midpoint of the overlap because the two tubes are of different diameter and hence of different stiffness. The highest stresses occur at the end of the overlap where the smaller tube is loaded. Adams and Peppiatt [39] also obtain stresses due to an applied torque on the joint. The tangential shear stress has very high values or concentrations at the ends of the overlap; however, no significant normal stresses are present.

4) Tubular Butt Specimens in Torsion and Combined Torsion/Axial Load - Ikegami et al [42] have used the tubular butt specimen shown in Fig.5.2c to obtain adhesive bond strength under combined shear (from a torque) and axial loading. Fig.5.8 shows typical results of their experiments; failure envelopes for arbitrary combined stresses. It is believed that tubular butt specimens are an effective way to obtain realistic strength data.

It is important to note that stress analyses of "doubler plates" subjected to an applied axial load, as shown in Fig.5.9

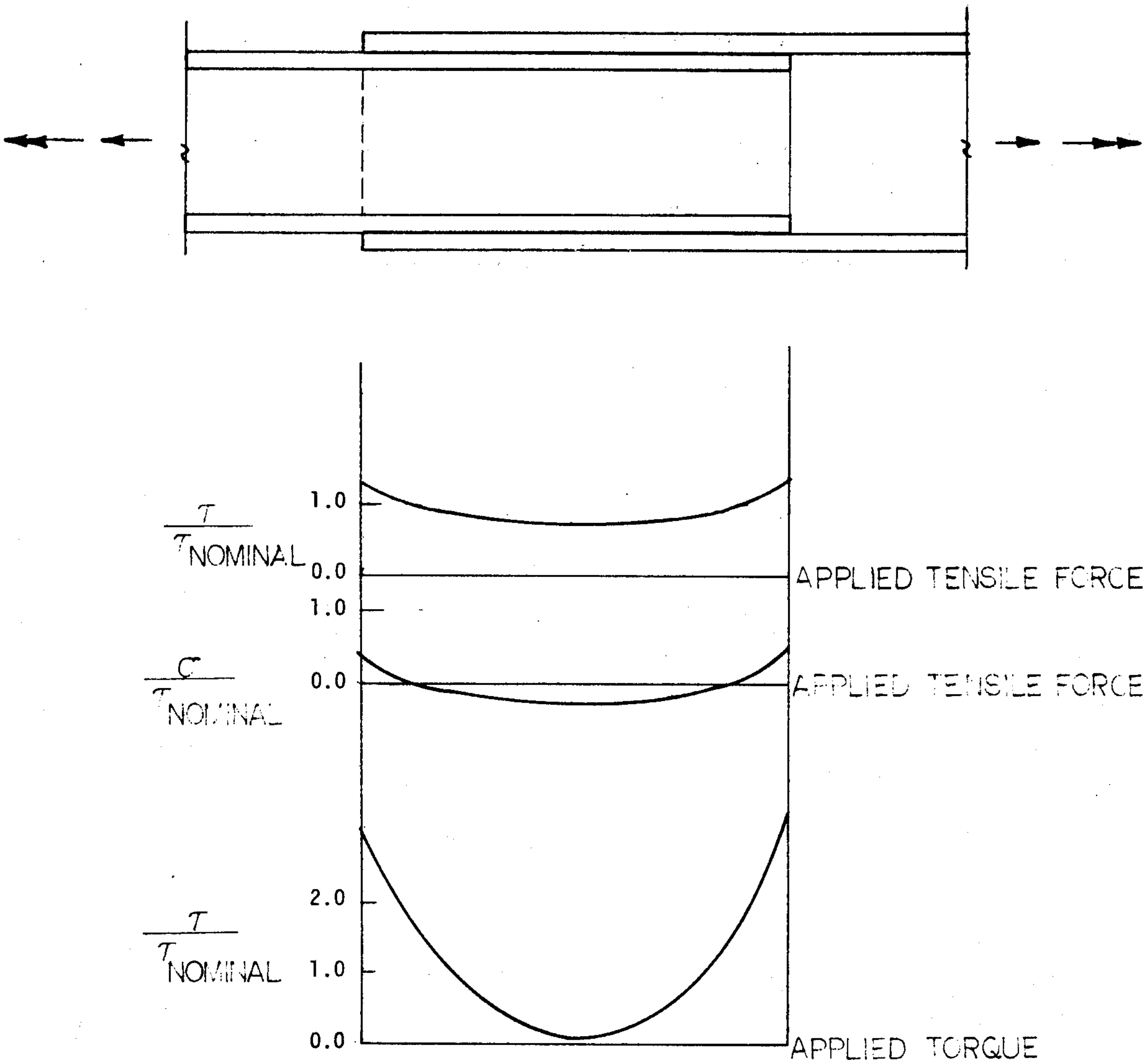


FIG. 5.7 TUBULAR LAP JOINTS

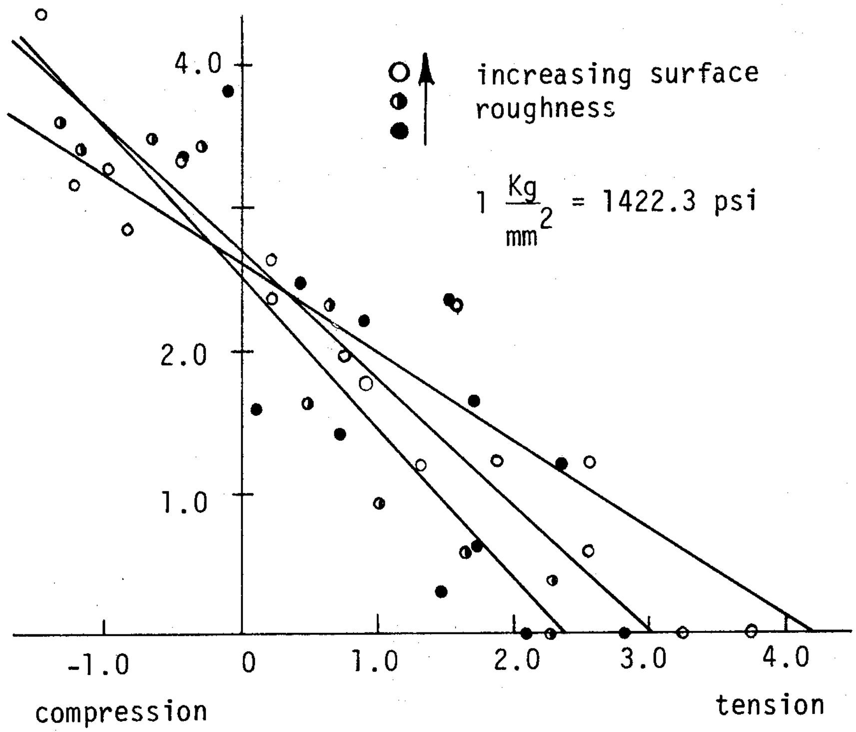


FIG. 5.8 STRENGTH OF TUBULAR BUTT JOINTS SUBJECTED TO COMBINED TENSION AND SHEAR REF. (42)

have been done [ ], [ ], [45]. Although such a bonded geometry is not used for obtaining bond properties, Fig.5.9 indicates that the configuration is analogous to the condition of having a vertical angle or tee stiffener bonded onto a flexural member. Fig. 5.9a, adapted from Yuceoglu and Updike 1451, indicates that axial load is transferred to the doubler plate by shear stresses primarily at the ends of the plate. Because of asymmetry, bending of the adherend and normal stresses do occur. Such normal stresses significantly affect static and fatigue bond strengths.

Preliminary Evaluation of Structural Adhesives - After examination of the information received from 39 manufacturers, 11 adhesives were obtained for preliminary evaluation. As noted, the stress conditions in a single lap shear test are very complex, therefore, although it is a widely reported ASTM standard test, it was not used for evaluating adhesives. Rather, double lap tension shear tests were used. They are relatively easy to bond and do not require the production of machined test pieces.

The double lap shear specimens consisted of two 1/8" thick, 1" wide steel flats adhesively bonded to each side of a third 1/8" thick by 1" wide steel with a ½" bond overlap as shown in Fig.5.5. The nominal bond area was 1 in^2. The thickness of the adhesive bond was controlled at 0.010" by inserting two 0.010" copper wires across the bond area to maintain this thickness as the flats were spring clamped together during bonding. This bond area was grit blasted to remove mill scale and then

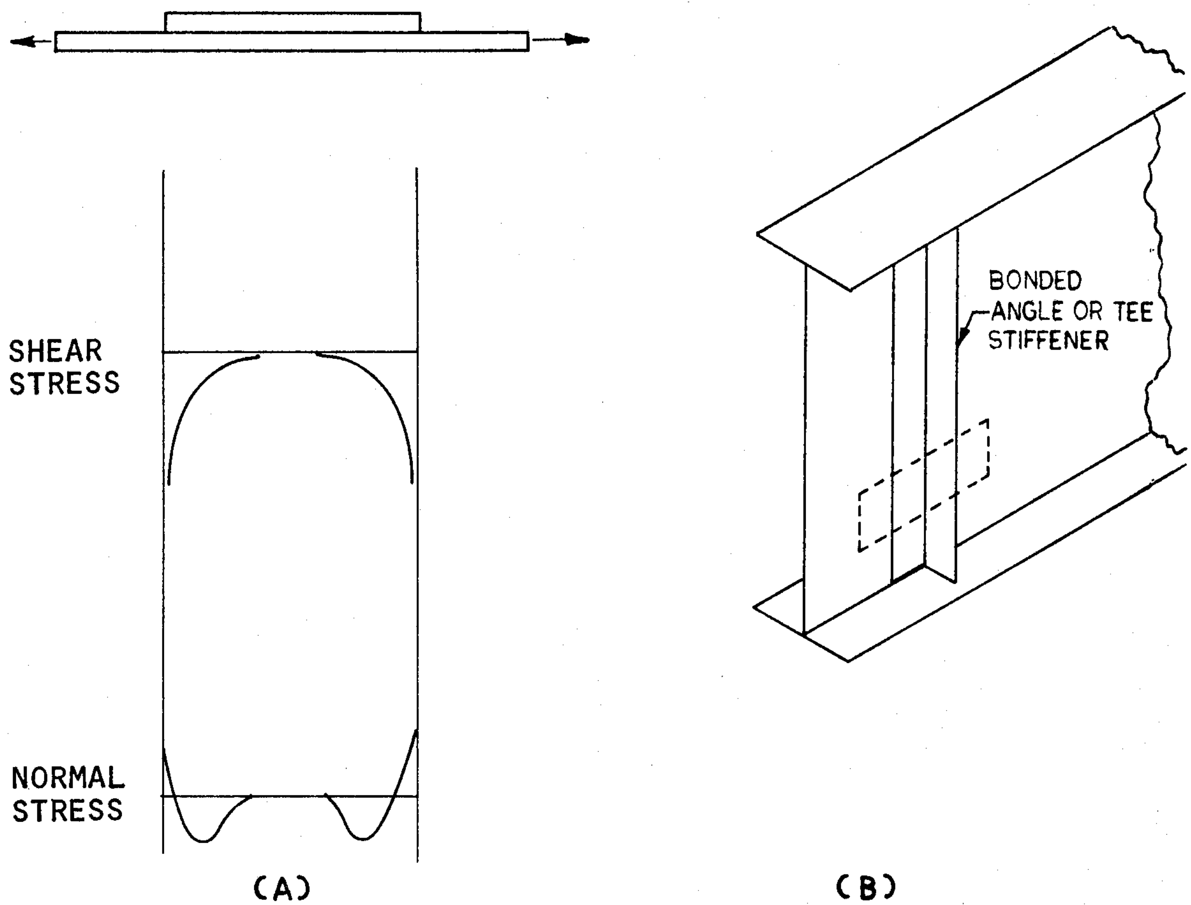


FIG. 5.9 STRESSES IN "DOUBLER PLATE" JOINTS; ANALOGY TO STIFFENER BONDED ON BEAM

cleaned with MEK before the adhesives were applied in accordance with manufactures' specifications.

A few tension tests were conducted half was essentially "T" shaped with a 1 in^2 bond area as shown in Fig.5.10. The adhesive's thickness was maintained at 0.010" as in the case of the double lap shear tests.

In both the tension tests and the double lap shear tests, loads were applied to failure at a rate of 1200 to 1400 lbs/in^2 per minute with a universal testing machine.

Double lap shear tests were conducted at $-40^{\circ}F$, room temperature and $150^{\circ}F$ for all candidate adhesive materials. Low temperatures were achieved by placing the specimens over ethylene glycol, cooled by using CO_2. Elevated temperatures were obtained by placing specimens in an oven. As soon as a specimen was ready for testing, it was removed from the heating/cooling position, wrapped in insulation and tested. Tension tests for four adhesives were performed at room temperature.

Table I shows the adhesives tested. Adhesives are identified as to class, form, cure and some performance characteristics. Table 5.2 shows the results of the ultimate strength tests. In most cases two specimens were tested under each condition for each material.

Lord Versilok 204, Dexter Hysol EA934 and Dexter Hysol EA9309 were selected for further investigation. Lord Versilok 204 was chosen for its high shear and tensile strength, ability to cure rapidly at room temperature and apparent insensitivity to oil contaminated surfaces. Lord Versilok 204 was selected over Lord Versilok 201 for its higher viscosity which assures better adhesive retention on

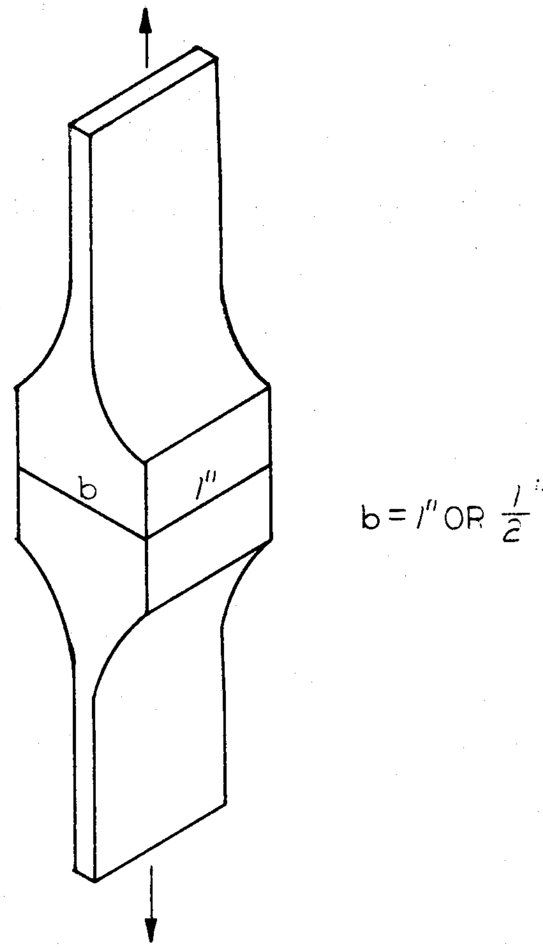


FIG. 5.10 TENSILE SPECIMEN

vertical surfaces or where uneven surfaces require the maintenance of a thicker adhesive layer.

Dexter Hysol EA934 and Dexter Hysol E9309 were selected as they appeared to be the best of the epoxy based adhesives tested. The epoxy adhesives have been in use for an extended period of time and it was deemed important to compare the newer acrylic adhesives with an epoxy not only for the purpose of relative performance but because substantial data is available on epoxy adhesives, therefore a secondary check on test results is possible.

TABLE 5.1

Candidate Adhesives

ADHESIVE	CLASS	FORM	CURE	CHARACTERISTICS
Dexter-Hysol EA-934	Epoxy	Two Part Mixture	5-7 days @ R.T. 1 hr. @ $200^{o}F$	-Used on Bridges for Bonding Teflon to Steel -Contains asbestos
Dexter-Hysol EA-9309	Epoxy	Two Part Mixture	1-3 days @ R.T.	-Good Peel Strength -Contains Asbestos Fiber
Dexter-Hysol EA-9330	"Modified" Epoxy (contains rubber)	Two Part Mixture	3 days @ R.T. 1 hr. @ $250^{o}F$	-High Peel Strength -Good Environmental Durability
Narmco Metlbond 1113	"Solids" Modified Epoxy	Primer and Supported Film	Primer 1 Hr. @ $250^{o}F$ Epoxy 1 Hr. @ $260^{o}F$	-Used Widely in Aerospace
Armstrong A-12	Epoxy	Two Part Mixture	1week @R.T. 1 Hr. @ $200^{o}F$	-Mix Ratio is Flexible
Armstrong A-39	Epoxy with inert fillers modified polyamine curing agent	Two Part Mixture	1 Hr. @ $160^{o}F$	-Meets MMMA-134
B.F.G. A-1273	Epoxy	Two Part Mixture	2-3 days @ R.T. 1 Hr. @ $160^{o}F$	-Meets MMMA-134 -Honey-like Viscosity
B.F.G. A-1177-B	Epoxy	Two Part Mixture	2-3 Days @ R.T. 1 Hr. @ $160^{o}F$	-Meets MMM A-134 -Highly Viscous
Loctite 324	Methacrylate Ester (Base)	No Mix Spray On Activator	<24 Hrs. @ R.T. 75% of strength in 2 hours	-Good Elongation
Lord Versilok 201	Acrylic	Accelerator and Paste Adhesive	15 min. @ R.T.	-Minimal Surface Preparation -Odor Extremely Irritating
Lord Versilok 204	Modified Acrylic	Accelerator and Paste Adhesive	15 min. @ R.T.	-Minimal Surface Preparation -Odor Extremely Irritating

TABLE 5.2

Double Lap Shear and Tensile

Test Results

ADHESIVE	STATIC DOUBLE LAP SHEAR STRENGTH- psi			STATIC TENSILE STRENGTH-psi	
	-40°F	Room Temperature	+150°F	-40°F	Room Temperature
ARMSTRONG A-12	2740 2070 2400	2760(2) 2760	430 620 520		
ARMSTRONG A-39	2160 2930 2540	2730 2730	2870 3710 3290		
LORD-VERSILOK 201	6340 6500 6420	3820(2) 3820	2220 2360 2290		2860 3760 3310
LORD-VERSILOK 204	5730 4070 4900	3830(2)* 3930 3880	2270 2370 2320		3390 3710 3550
B.F.G.-A-1273	1830 1750 1790	3125(2) 2970 2820	2120 2850 2480		1860 1640 1750
B.F.G. A-1177	1470 1480 1470	2860 2860	3640 3350 3500		1550 1120 1330
NARMCO-METLBOND 1113	4190 3370 Avg 3780	3200(2)	2560		
DEXTER HYSOL-EA 934	2650 2420 2530	3555(2) 3550	2360 1620 1990		
DEXTER HYSOL-EA-9309	5010 5810 5410	3850(2) 3560 3700	1000 810 900		
DEXTER HYSOL EA-9330	5620 5810 5680		430 490 460		
LOCTITE -324	2180 2180		500 530 510		

*Steel Failure

(2) Two inch overlap
All others one inch

Stress-Strain Characteristics of Dexter-Hysol EA9309 and Lord Versilok 204

A detailed understanding of the stress-strain behavior of adhesives can provide useful insights into the behavior and durability of adhesive joints. Adhesive bonds introduce into a structure thin layers of material with entirely different stress-strain, time-temperature characteristics than the parent material of the structure. The behavior of these adhesive joints within a structure not only affects the ability of the structure to carry static and dynamic loads but affects the structural behavior of the structure.

Modulus of Elasticity Using Bulk Specimens - Dogbone-shaped specimens were machined from bars cast of Dexter-Hysol EA9309. Strains were measured with a mechanical extensometer as the specimen was loaded in tension. The results are displayed in Fig. 5.11. The moduli of elasticity E for each of the two specimens tested were 0.29×10^6 and 0.33×10^6 psi respectively. Although manufacturer's data was not available for comparison, these results are on the low end of values for typical unmodified epoxy resins. Errors in these values can also be the result of the non-averaging nature of mechanical extensometers and the tendency to entrain air during the preparation of the adhesive for casting.

No tests were conducted on Versilok 204 because its short pot life and high viscosity made it impossible to cast a suitable specimen for testing by ordinary techniques.

Apparent Modulus of Elasticity from Tensile Tests of Bonded Specimens - As noted, an attempt was made to measure strains in the adhesive by placing a 1/8" long, post-yield, resistance-type gauge directly over the adhesive

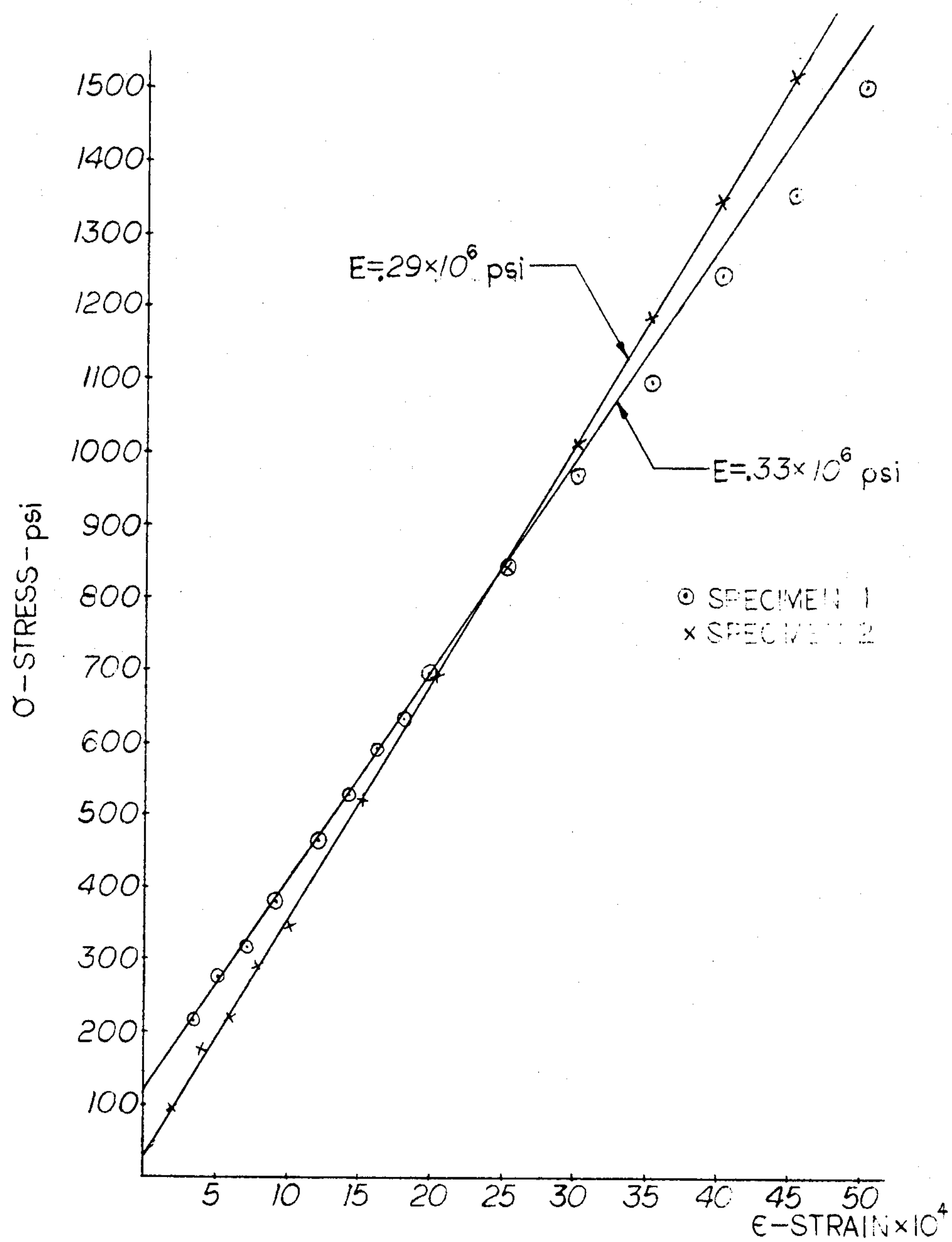


FIG. 5.11 TENSILE STRESS STRAIN CURVES
FOR BULK EA 9309 SPECIMENS

bond line of the ASTM D897 spool type tensile specimens. The standard ASTM D897 fixtures were used to apply tension loads to the specimen. To apply compression loads the spool was simply inserted between the testing machine heads, one of which had a spherical bearing. Eq. 5.2 (p.67) indicates the calculation required to compute the strain in the adhesive material from the strain recorded by the gauge. As discussed on p. 63, the apparent modulus of elasticity of an adhesive in a thin layer within a joint is larger than that of a bulk adhesive specimen because the lateral deformation of the adhesive is restrained by the much stiffer adherend material. Eq. 5.1 gives the expression for the apparent modulus E^*.

Fig.5.12 shows the composite results of several compressive load stress strain curves for both the EA9309 and the Versilok 204 adhesive joints in the ASTM D897 specimens. E^* for EA9309 from these tests is 0.510×10^6 psi and for Versilok 204 the apparent modulus is 0.490×10^6 psi. Table 5.3 shows the values of the actual modulus of elasticity, E, (computed by Eq. 5.1) for an apparent modulus E^* of 0.500×10^6 psi and for a range of Poisson's ratios.

TABLE 5.3

BULK MODULIS vs-ν FOR Ea=0.5×10^6 psi

Poisson's Ratio	E (for $E^*=0.5 \times 10^6$ psi)
0.25	0.42×10^6 (psi)
0.30	0.37×10^6 (psi)
0.35	0.31×10^6 (psi)
0.40	0.23×10^6 (psi)

The average moduli of elasticity from bulk specimens of EA9309 was measured as 0.31×10^6; this value with $E^*=.5 \times 10^6$ psi would correspond to

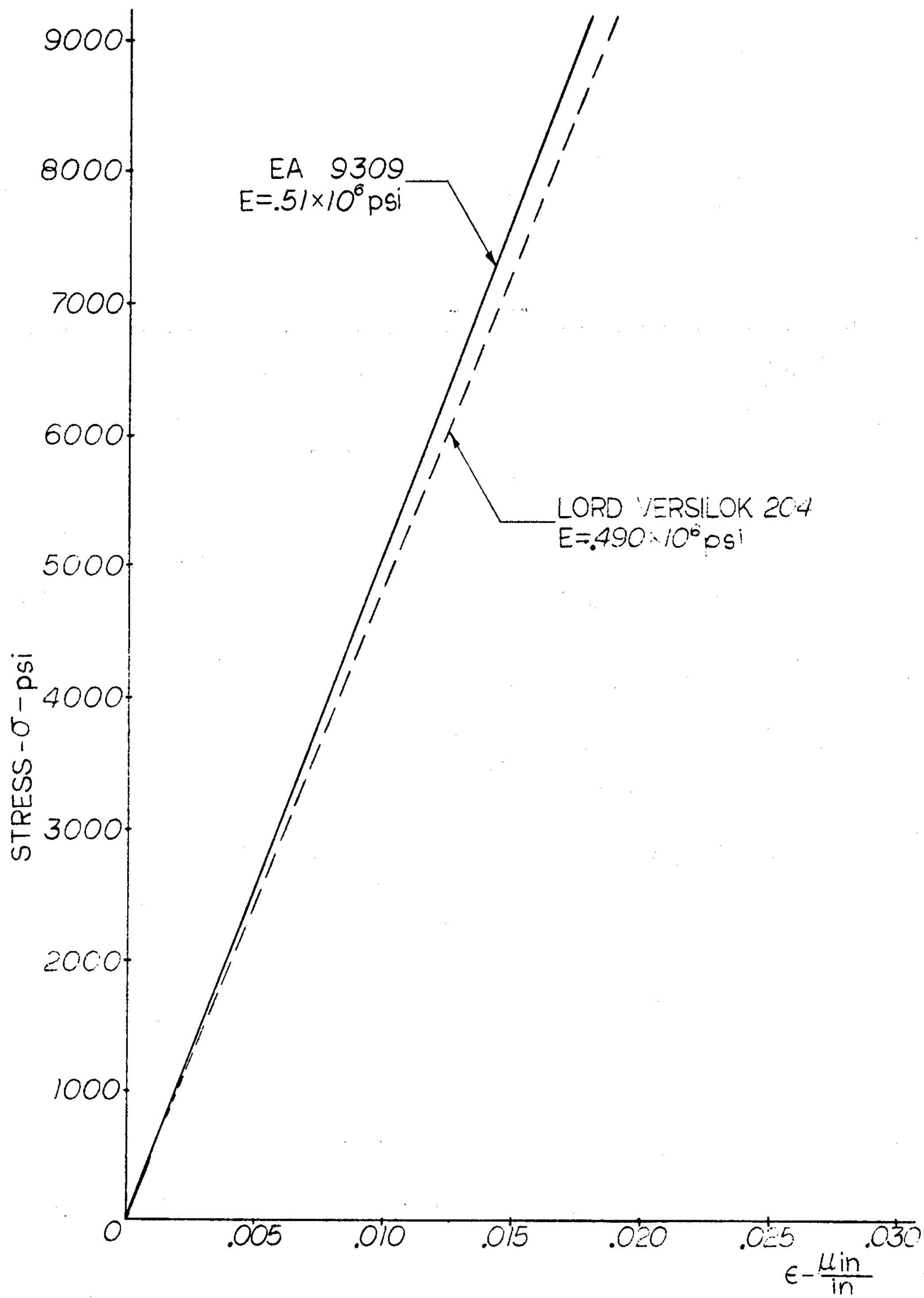


FIG. 5.12 COMPRESSIVE STRESS–STRAIN CURVE USING ASTM D 897 SPECIMENS

a theoretical Poisson's ratio of about 0.35 which is in the range of normally expected values.

Fig.5.13 shows the composite results of several tensile shear-strain curves for both the EA9309 and the Versilok 204, ASTM D897 specimens. These specimens were loaded using the ASTM D897 tension fixtures which, as noted on p. 68, do not provide concentric loading.

The apparent elastic modulus from these experiments is about $1. \times 10^6$ psi for both adhesives which, for $\nu=0.35$, implies a modulus of elasticity (from Eq. 5.1) of $.62 \times 10^6$ psi. Both adhesives showed a definite yield stress, however the value of stress at yield and the shape of the stress-strain curve in the transition to ideal plastic behavior was very dependent on loading rate, which was not strictly controlled.

The following observations summarize the results of the tests on ASTM D897 specimens

1. The apparent modulus E^* obtained from the compression tests appears to be within accepted values .
2. The stress-strain curves in compression are linear for values of stress in excess of 10,000 psi.
3. The apparent modulus E^* obtained from the tension tests was much larger than that obtained from compression tests. The actual reasons for this have not been definitely identified.
4. In tension the adhesive joints exhibit a marked yield, however the magnitude of the yield stress and the detailed shape of the stress-strain curve is dependent on the loading rate.
5. The ASTM D897 specimen and fixtures do not appear to be suitable for tension experiments to determine stress-strain characteristics of the adhesive joint. A carefully designed loading fixture and specimen to assure load concentricity and well controlled loading rates are required for useful results.

   shorter gauges would improve the accuracy of the strain measurements.

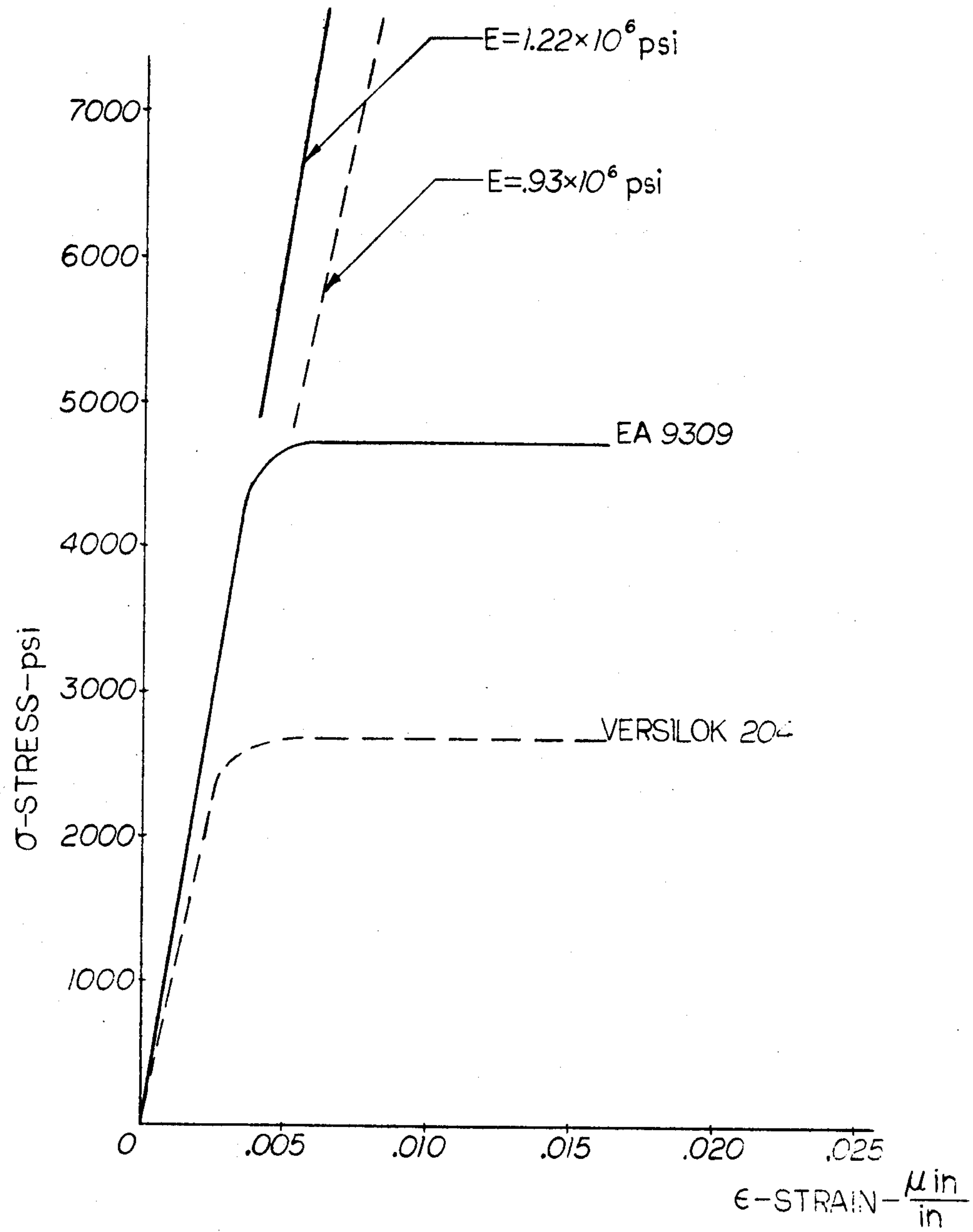


FIG. 5.13 TENSILE σ-ε CURVE FROM ASTM D 897 SPECIMENS

Apparent modulus from bending tests - An 8" long rectangular steel bar of 1" x 2" cross section was cut normal to its longitudinal axis at its midlength and adhesively bonded together to form a 0.010" thick joint at midlength as shown in Fig.5.14. A 0.25" long resistance strain gauge was bonded to the top and bottom of the beam at midwidth and centered over the adhesive joint.

Fig.5.15 is a plot of strain gauge readings vs. bending moment. For moments up to approximately 2500 lb -in, the strains are linearly proportional to the bending moments. If one assumes that, for moments up to 2500 lb -in , the adhesive joint deforms and is stressed in accordance with elementary beam bending theory, then it is possible to calculate the normal stress in the adhesive. In addition it is reasonable to expect that the normal stress in the steel adjacent to the adhesive joint is the same as the normal stress in the adhesive. The thickness of the adhesive joint is known (0.01") and the modulus of elasticity of the steel is known therefore it is possible to calculate the strain in the adhesive at the 2500 lb.in. moment level.

The apparent modulus of the adhesive E^* is given by:

$$E^* = \frac{1}{\dfrac{25\varepsilon_s}{\sigma_a} - \dfrac{24}{E_s}} \tag{5.3}$$

where

E^* = apparent modulus of elasticity of adhesive in joint

σ_a = calculated normal bending stress

E_s = modulus of elasticity of steel

ε_s = steel strain

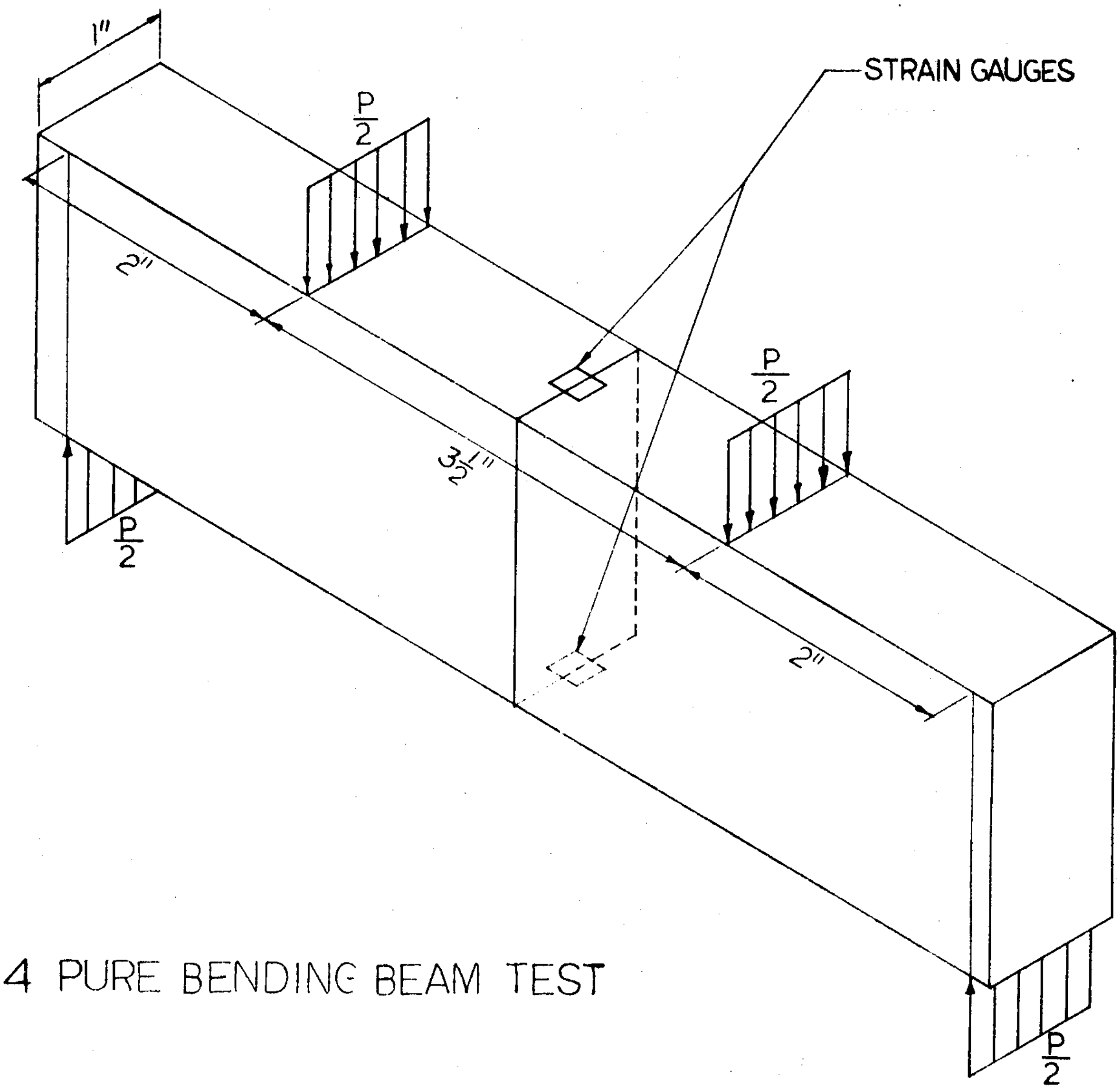


FIG. 5.14 PURE BENDING BEAM TEST

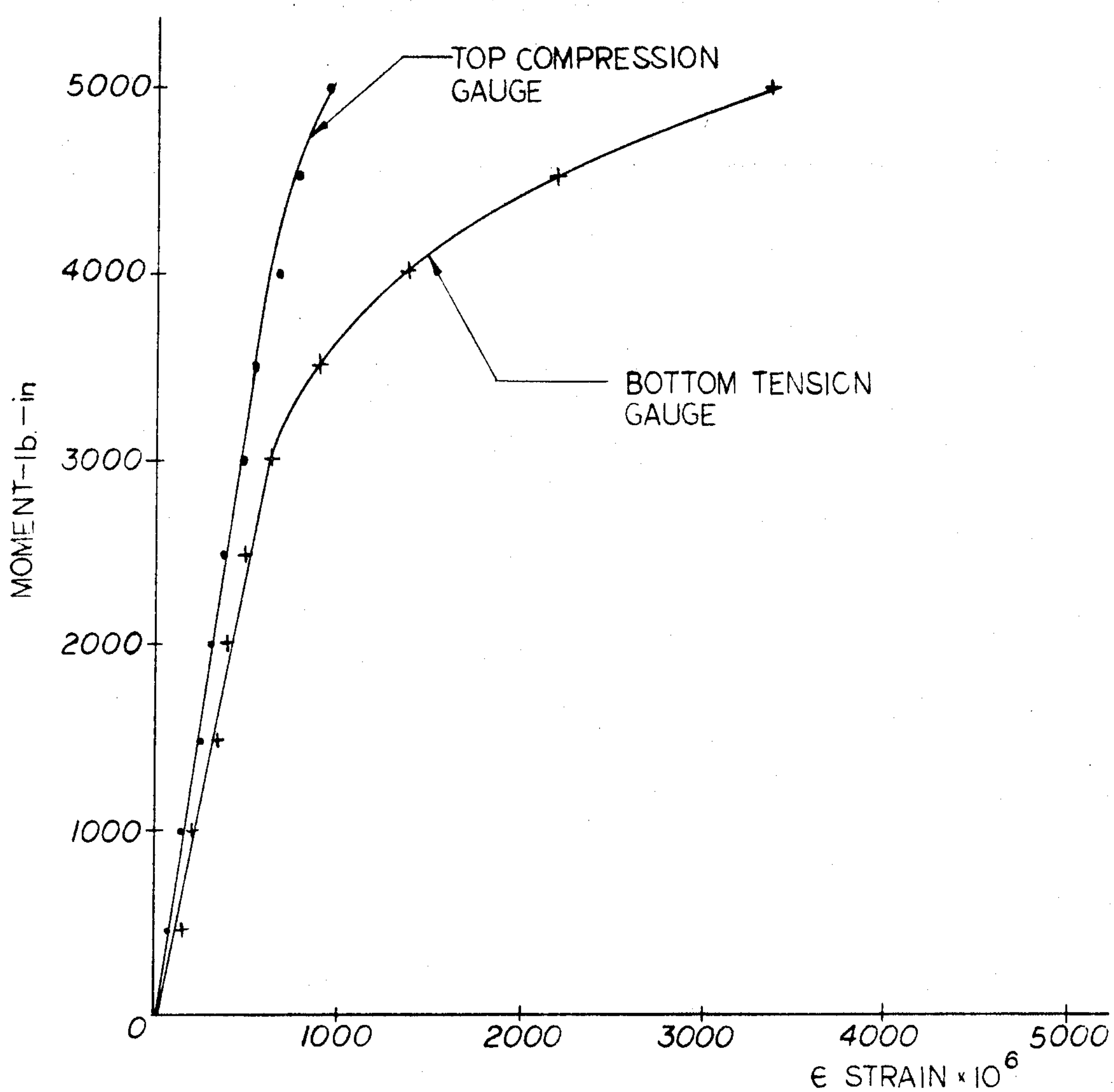


FIG. 5.15 STRAIN VS. BENDING MOMENT
VERSILOK 204

At 2500 lb. in. the theoretical bending stress is 3750 psi and using an average of the top and bottom strains of $454.\mathrm{x}\ 10^{-6}$ in/in the calculated value of E^* is 0.45×10^6 psi which compares favorably with a value of 0.49×10^6 psi observed in the compression tests on ASTM spools.

The assumptions made regarding the flexural stress distribution are supported by data taken from more extensive bending tests. Those tests are discussed in the next section.

<u>Bending Experiments</u> - The previously described tension and compression experiments on adhesive joints of Dexter Hysol 9309 and Lord Versilok 204 indicated the following characteristics for these adhesives when subjected to nominally normal stress fields.

1. The compression stress vs strain curves were essentially linear to stresses in excess of 10,000 psi.

2. The tension stress vs. strain curves were essentially of an elastic plastic nature with the yield stress observed highly dependent on rate of load application. As previously discussed, the use of the ASTM D897 to obtain quantitative stress-strain data is suspect but the general observation is probably valid.

Such observations indicate that an adhesive joint in pure bending would, at ultimate load conditions, have an elastic stress distribution on the compression face and some nonlinear distribution of the stress on the tension face.

At the ultimate load, the compression stresses can be expected to be substantially larger than the maximum tensile stress and, as a consequence of the yielding of the adhesive on the tension face, the neutral axis would be above the midheight of a beam of rectangular cross section. The most simplistic approach is to assume the compression force of the resisting moment couple to act at the top edge of the beam. Then, by assuming various stress distributions for the tensile stress field, simple relationships of the ultimate tensile strength of the adhesive to the applied moment can be developed. In general these relationships are of the form

$$M_u = K \sigma_u b h^2 \tag{5.4}$$

where

M_u = Bending moment at rupture (lb-in)

σ_u = Ultimate tensile strength of adhesive (psi)

b = width of beam

h = height of beam

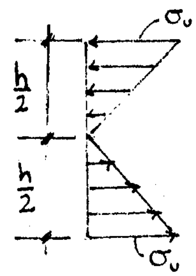
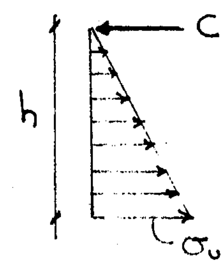
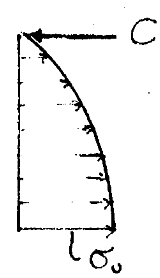
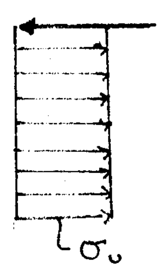
K = Dimensionless coefficient

Table 5A lists various assumed stress distributions for the tension fields. The first case shown is the linear stress distribution of elementary beam bending theory.

TABLE 5.4

VALUES OF K FOR VARIOUS TENSION FIELD STRESS DISTRIBUTIONS

where $M_u = K\sigma_u bh^2$

Stress Distribution	Sketch	K
1. Linear-compression and tension (elementary beam theory)		0.167
2. Linear-tension side		0.333
3. Second order parabolic tension side		0.417
4. Constant σ_u Tension side		0.500

To determine if the actual adhesive behavior tended toward any of the distributions shown in Table 5.4, rectangular beams of various widths and depths were bonded together at midlength with Dexter Hysol EA 9309 and Lord Versilok 204 and loaded to failure in pure bending. The loading geometry is shown in Fig.5.14. Table 5.5 shows the test results along with calculated values of "K" for various values of σ_u.

TABLE 5.5

K FOR EA 9309 & VERSILOK 204 BENDING TESTS

SPECIMEN GEOMETRY b" x h"	$\frac{M_u}{bh^2}$ (lb/in^2)		K		
			EA 9309		VERS 204
	EA 9309	Vers. 204	σ_u=4100	σ_u=6000	σ_u=4200
1 x 1	1560	1210	0.38	0.26	0.30
2 x 1	1620	1170	0.40	0.27	0.29
1 x 1.5	1920(2)	1030(2)	0.47	0.32	0.26
1 x 2.0	1684(2)	1316(2)	0.41	0.28	0.33
		Avg.	0.42	0.28	0.30

( ) No. of tests averaged

The ultimate values of the bending moments in these experiments are no doubt rate sensitive but since these were exploratory experiments conducted early in the investigative program the rates of loading were not controlled. In general failure occurred in less than one minute from the onset of loading.

The results indicate that the stress distribution at failure is not linear as evidenced by values of K substantially in excess of 0.167 for

reasonable values of σ_u. The values of K range from 0.28 to 0.42 depending on the value of σ_u assumed but are fairly uniform in each set of experiments. The values of σ_u of 4100 psi and 4200 psi are the ultimate tensile strengths of EA 9309 and Versilok 204 as obtained from the ASTM D 897 tension tests. Since there is some evidence (from bending tests to be discussed in the next section) that σ_u for EA 9309 might be as high as 6000 psi, this value was also used in calculating values of K from the EA 9309 data.

Stresses in Adhesive Joint Under Pure Bending - A steel beam 0.88" wide and 1.92" deep was instrumented with a set of resistance type strain gauges of 1/8" gauge length located as shown in Fig.5.16 adjacent but not over the bond line. The assumption was that the stresses in the steel adjacent to the bond line , which could be obtained from the experimental data, were essentially the same as those of the adhesive. Gauges 1 and 5 are located at midwidth at the top and bottom of the beam respectively, gauge number 2 is 0.2" down from the top of the beam and gauges 3 and 3A are 1.2" down from the top.

Figs.5.17 and 5.18 show measured stresses vs. the applied bending moment. The subscripts on the stresses correspond to the gauge numbers; σ_3 is the average stress as measured by gauges 3 and 3A.

Both figures are very similar but for Fig.5.17 will be used as a reference for the following discussion.

All stresses are linearly related to the applied bending moment until the range of 2-3000 lb - in. The stresses in gauges 1 and 5 (top and bottom) are nearly the same in the elastic range and reasonably close to the theoretical stress calculated from elementary beam theory.

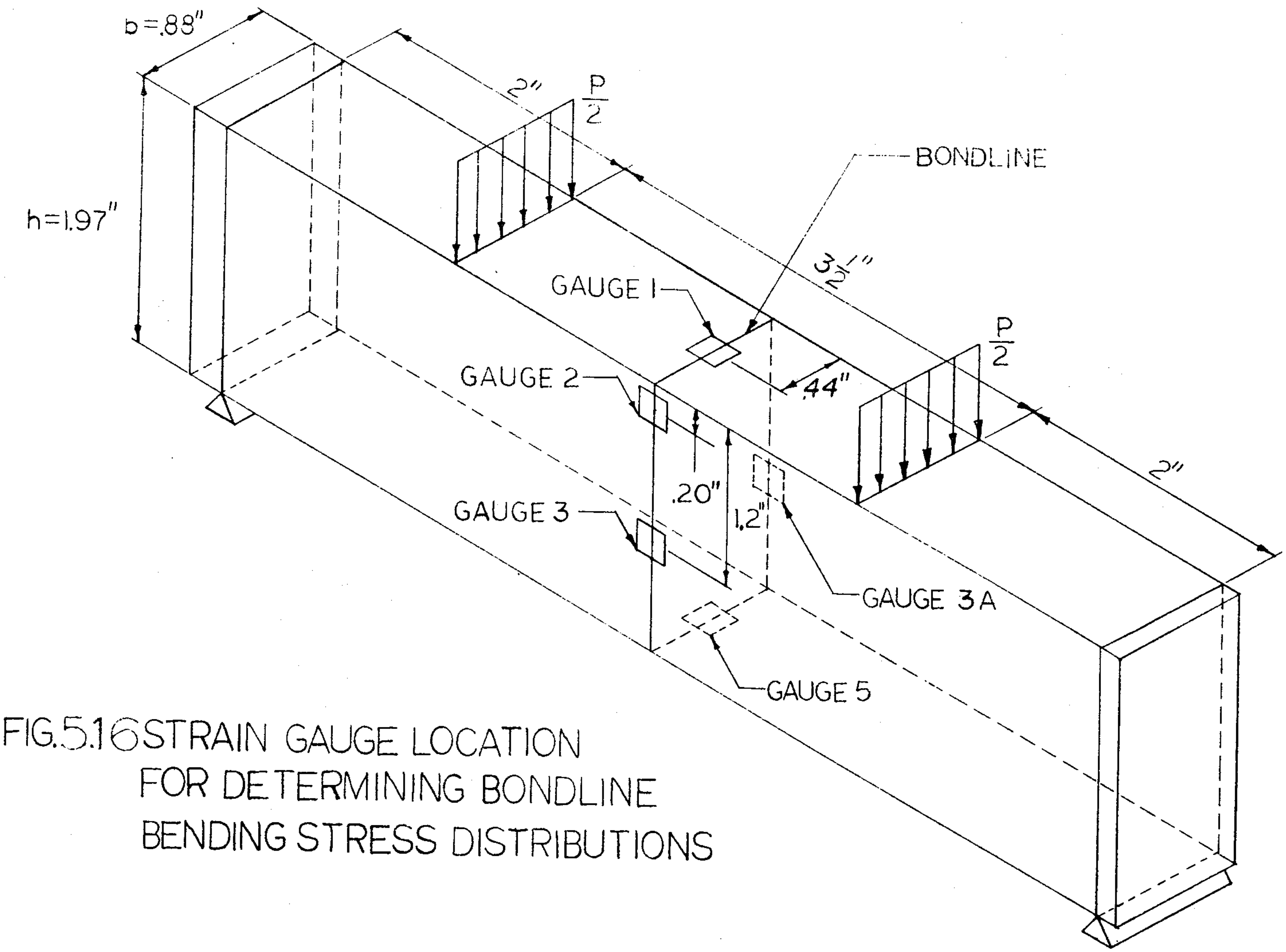


FIG.5.16 STRAIN GAUGE LOCATION FOR DETERMINING BONDLINE BENDING STRESS DISTRIBUTIONS

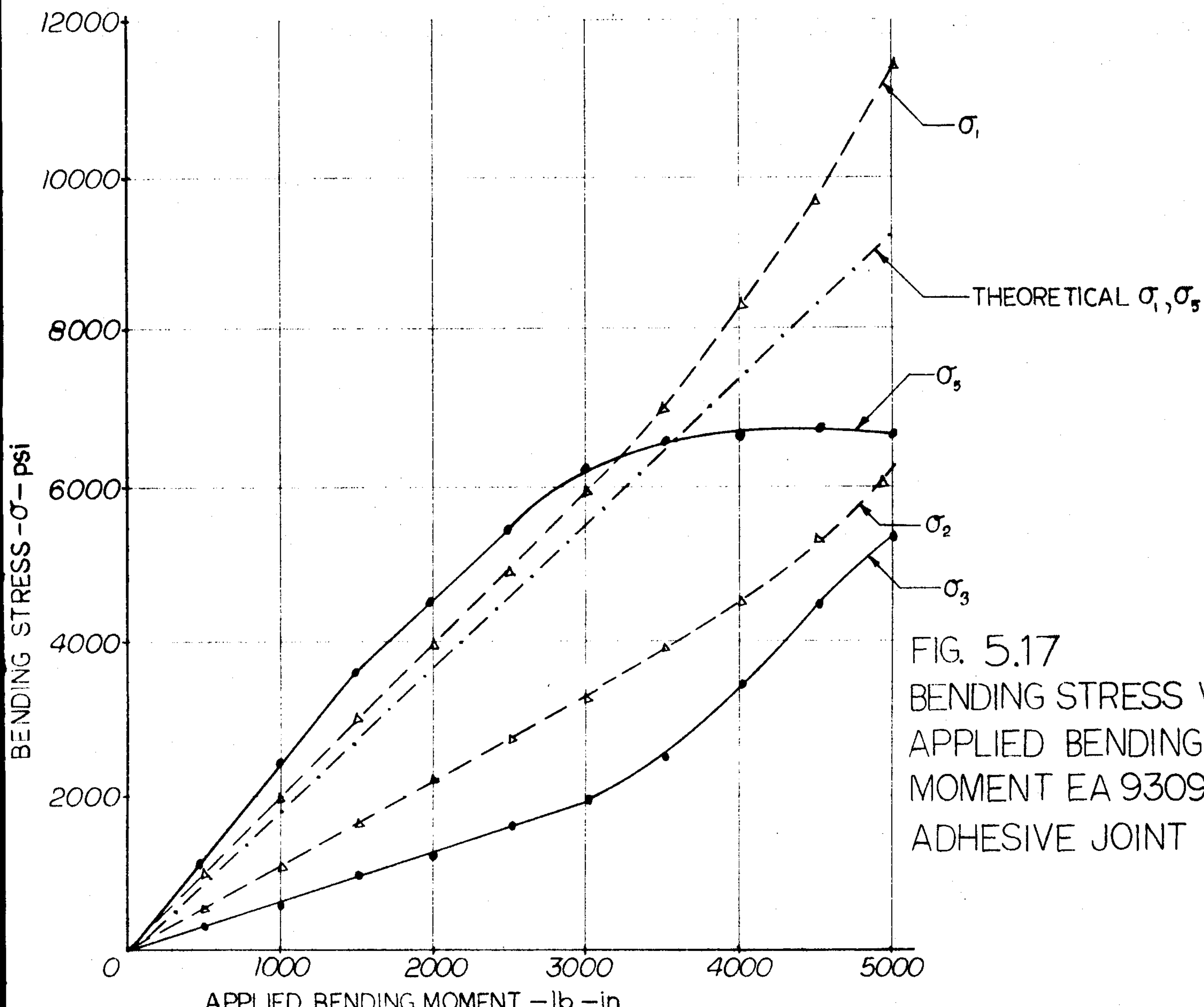


FIG. 5.17
BENDING STRESS VS. APPLIED BENDING MOMENT EA 9309 ADHESIVE JOINT

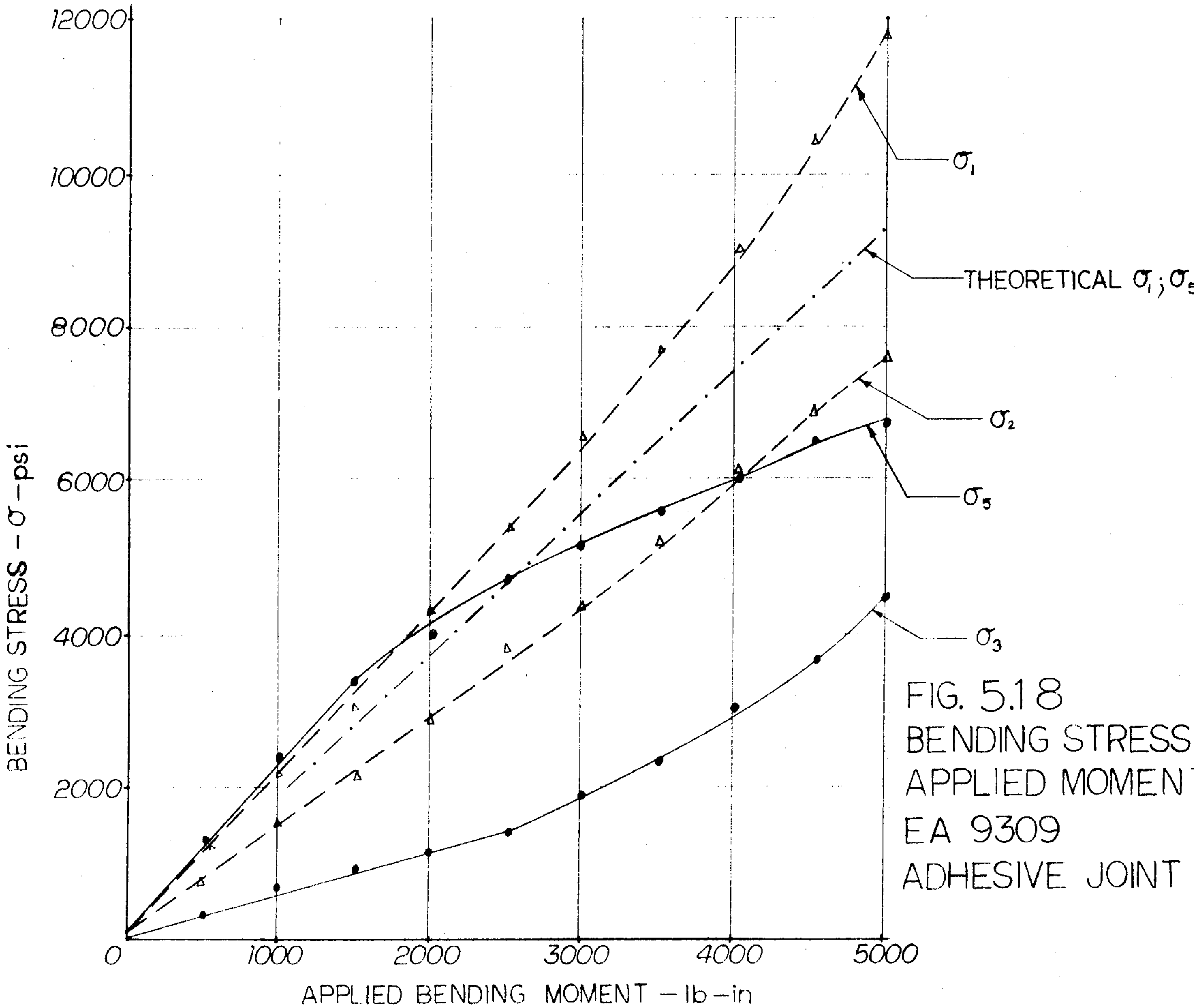


FIG. 5.18
BENDING STRESS V[S]
APPLIED MOMENT
EA 9309
ADHESIVE JOINT

When the adhesive on the tension side (bottom) of the beam begins to yield the stress at location 5 is no longer proportional to the applied moment. When yielding occurs the stress in location 3 rises more rapidly than at a linear rate and if ideal elastic plastic behavior is evidenced on the tension side then σ_3 should approach σ_5 assuming large enough strains can be accommodated at location 5 before fracture.

When yielding occurs at the bottom of the beam we would expect σ_1 and σ_3 to increase at a rate greater than their linear rate before yielding occurred.

All the previous observations are confirmed in both Fig. 5.17 and Fig. 5.18.

It is also interesting to note that the maximum tensile stress in the EA 9309 adhesive at the bottom of the beam approaches 6600 psi, far in excess of the 4100 psi obtained from the ASTM D987 experiments. This result tends to confirm the observation of Skeist [78] previously cited.

Assume a stress distribution which is linear in the area of the compression stress field in the adhesive joint and constant in the tension stress field as shown in Fig. 5.19.

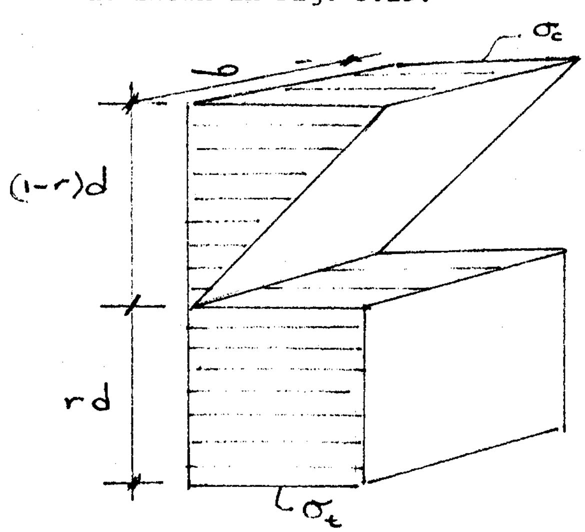


Fig. 5.19

From the requirement that the stress distribution must be such as to result in a pure moment then it can be shown that:

$$r^2 - 5r + 4 = \frac{12\ M_u}{\sigma_c\ bd^2} \qquad (5.5)$$

where

r = (see Fig. 5.19)

M_u = ultimate banding moment (lb-in)

σ_c = maximum compression stress (psi)

b,d = width and depth of beam respectively (in)

If one substitutes σ_c = 12000 psi at M_u = 5000 in lb. then $r = 0.5529$. From the requirement that the total compression force must be equal to the total tension force then σ_t = 4900 psi

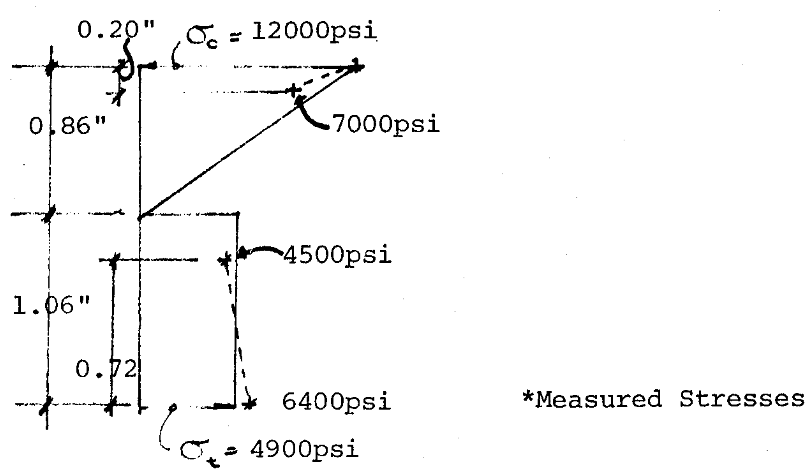


Fig. 5.20 Theoretical and measured stresses

Fig.5.20 shows the calculated stresses and the average of measured stresses from Figs. 5.17 and 5.18. There is insufficient data to make conclusive quantitative statements about the details of the stress

distribution. For the theoretical case cited above the equivalent K to those shown in Table 5.4 is 0.32. It does appear that the method has merit and in future experiments more gauges should be used and the rate of loading carefully controlled. These experiments were limited to the EA 9309 adhesive and should be rerun and extended to other adhesives such as Versilok 204. The experiments conducted here took approximately 15 minutes to complete.

There is a question about the validity of assuming that the stresses in the steel approach the stresses in the adhesive. The arguments supporting the assumption are as indirect as the measurements. The fact that the stresses adjacent to the bond are reasonably consistent with elementary beam theory at low values of the bending moment and that the stresses in the steel change at higher bending moments in a manner consistent with the expected behavior of the adhesive indicates that the measured stresses probably do show what nominally occurs in the adhesive joint.

Tension Tests - Tension tests of the Dexter Hysol EA 9309 adhesive and the Lord Versilok 204 were conducted in accordance with ASTM D 897 test procedures. The results are given in Table 5.6.

TABLE 5.6

ULTIMATE TENSILE STRENGTH (ASTM D879 TEST)

Adhesive	Avg. Ult. Tens. Stress (psi)	Std. Dev. (psi)	Coeff. of Variation %
Dexter Hysol 9309	4123(10)	364	8.8
Lord Versilok 204-Accel#4	3739(8)	171	4.6
Lord Versilok 204-Accel#5	4230(10)	444	10.5

( ) No. of Tests

Accel #4 Brushed on substrate
Accel #5 Mixed with adhesive

The results in Table 5.6 were obtained with the open sides of the test fixture both facing the same direction. The following results were obtained from an additional 5 tension tests run on Versilok 204 (accelerator #5) with the open sides of the test fixture located 180° apart:

Ultimate Tensile Strength	4400 psi
Standard Deviation	191 psi
Coefficient of Variation (%)	4.3

The results are not significantly different from the values in Table 5.6. The nature of the ASTM D879 fixture is such that no loading can be transferred to the rim of the spool in the open region of the fixture hence the diametrically symmetrical loading pattern required for concentricity cannot be achieved. Additional tension tests with loading rates of 1200-1400 psi/minute were conducted on adhesive joints made with Versilok 204, (accelerator #5) in ASTM D897 specimens, 1"x1" T specimens and 1"x1/2" T specimens. The T specimens were held by their stems in jaws terminating in spherical seats in a Universal testing machine. The results are shown in Table 5.7 and are surprising in that the rectangular specimens showed substantially lower strength than the ASTM D897 specimens. The spool specimens compared favorably with previous tension test results of 4230 and 4400 psi.

TABLE 5.7

ULTIMATE TENSILE STRENGTH

LORD VERSILIK 204-Accel #5

Adhesive	Avg. Ult. Tens. Stress (psi)	Std. Dev. (psi)	Coeff. of Variation (%)
ASTM D897	4400 (5)	191	4.3
1" x 1" Rect.	3360 (5)	208	6.2
½" x 1" Rect.	3230 (8)	227	7.0

There is no ready explanation for the decrease in strength from circular to rectangular specimens. On the contrary, it might be argued that the "T" specimens were probably loaded in a more concentric manner than the spool specimens. Perhaps the difference in the detailed stress distributions in rectangular vs. circular cross sections had a significant effect on the short term strength of adhesive joints in tension. This observed behavior requires further investigation.

Strength of Bonds Subjected to Sustained Tensile Loading - The tensile strength data reported in Table 5.7 were obtained using a loading rate of 1200-1400 psi/min. It was observed that when specimens were loaded at a slower rate the ultimate tensile stress decreased. This is not a new observation although there does not appear to be a great deal of data in the literature. Wangsness [83] shows data of average shear strength of single lap shear stress specimen vs time to rupture. It indicates that if fracture stress σ_f is plotted against the log of time at which fracture occurs a plot similar to that shown in Fig. 5.21 would be developed.

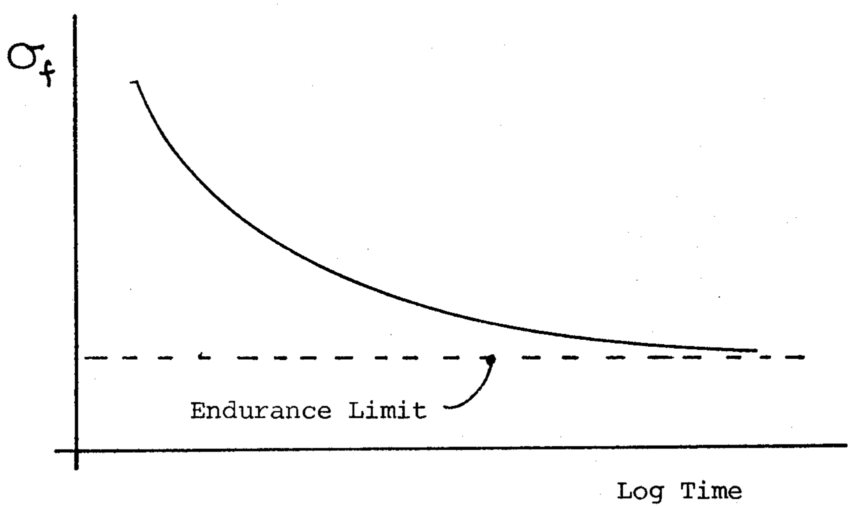


Fig. 5.21 Durability Curve Stress vs Log Time to Rupture

The expected curve is similar to the familiar fatigue curve of stress vs log cycles to failure where time now replaces the number of cycles to failure. The endurance limit is defined as the stress level below which indefinitely long life can be expected or, geometrically, the endurance limit is the stress level defined by a horizontal asymptote to the σ_f vs time curve. Whether a non-zero endurance limit exists in every case is open to speculation however the Wangsness [83] data suggests that testing for time periods of 600 to 1000 days may be required to establish its existence.

Versilok 204 with accelerator 5 and Dexter Hysol EA9309 were used for the sustained load experiments. The standard ASTM D897 specimens and fixtures were used for those stress levels where time to fracture was less than 10 minutes.

For stress levels which required longer periods of time to fracture it was necessary to change the specimen geometry because of the prohibitive cost of producing enough ASTM D897 test fixtures to get data in a timely fashion.

"T" shaped specimens with rectangular bond area of 1"x1" or 1"x½" were fabricated as shown in Fig. 5.10. A few tests were run loading the 1"x1" T-specimens by weights but laboratory space and safety dictated the use of springs in cylindrical fixtures as shown in Fig. 5.22

Fig. 5.23 and 5.24 show the tensile stress vs log time to fracture for the two adhesives. There appears to be no obvious discontinuity in the data for times to fracture greater than 10 minutes which would represent the transition from ASTM D897 specimens to rectangular specimens.

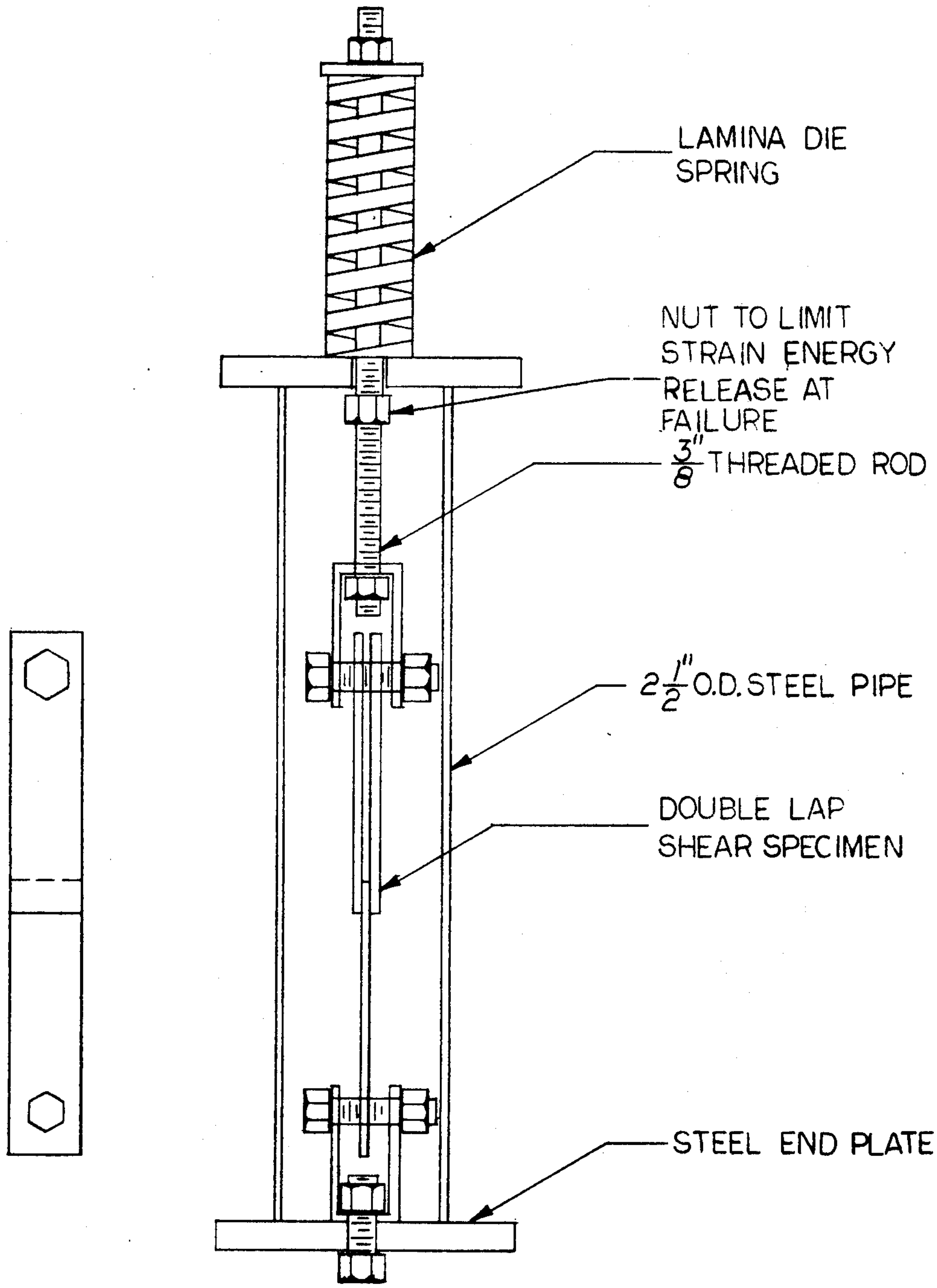


FIG. 5.22 STATIC FATIGUE APPARATUS

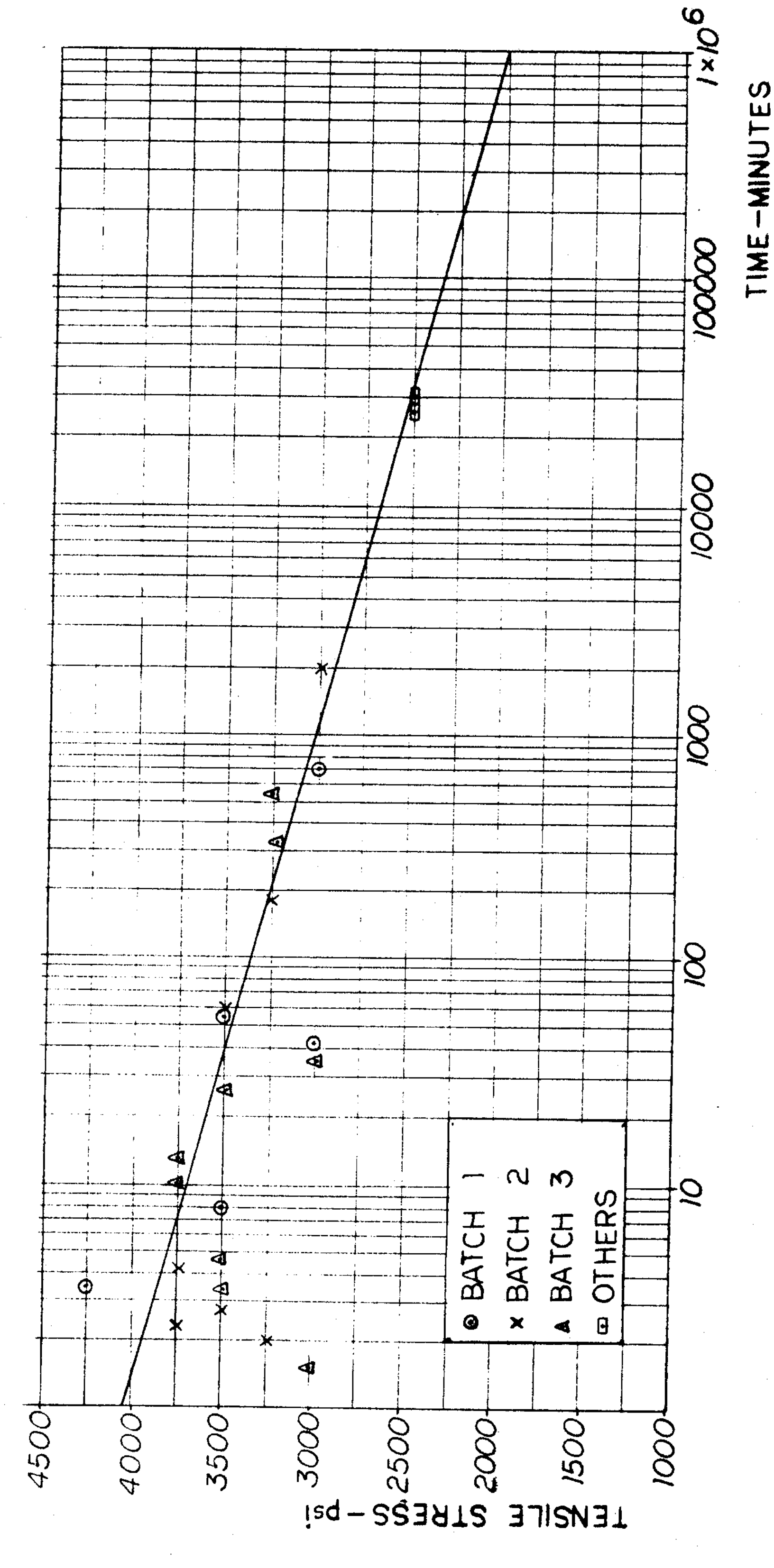


FIG. 5.23 TENSILE STRESS VS. TIME TO FAILURE FOR DEXTER-HYSOL EA 9309 BONDED SPECIMENS

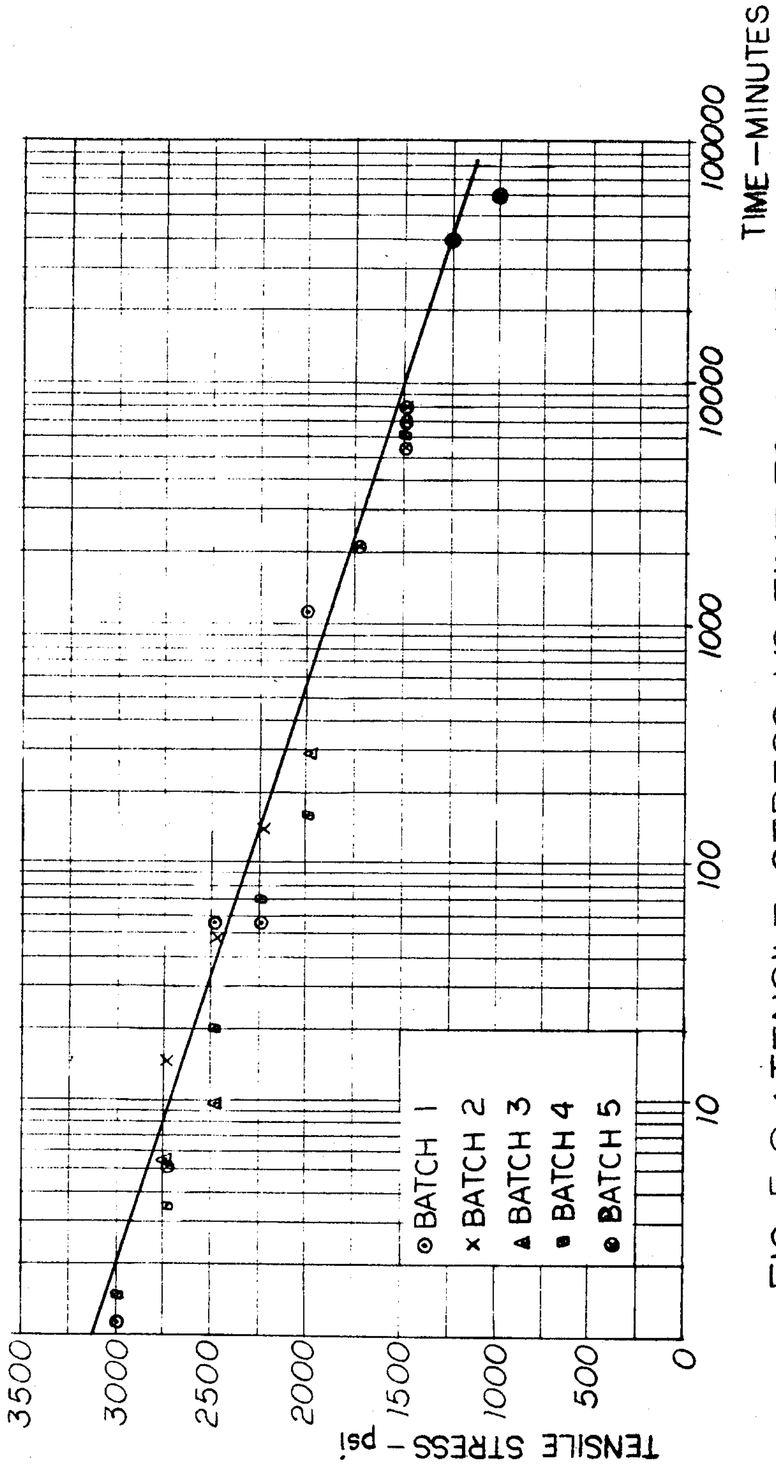


FIG. 5.24 TENSILE STRESS VS. TIME TO FAILURE FOR VERSILOK 204 BONDED SPECIMENS

The ultimate tensile strength data for times less than 100,000 minutes fits the form of the equation

$$\sigma_u = K - B \log_{10} T \tag{5.6}$$

where σ_u = ultimate tensile strength (psi)

K = constant (psi) essentially the short term ultimate tensile stress

B = constant

T = time to fracture in minutes

For Dexter Hysol EA 9309, K = 4100, B=380 and for the Lord Versilok 204, K = 3200, and B = 420.

As of August 4, 1981 two of four of the Dexter Hysol EA 9309 specimens stressed to 2500 psi and three of three specimens stressed to 2250 are still intact after 5.14×10^5 minutes. It appears that the endurance limit for the EA 9309 is being approached at 2000-2500 psi.

As of August 4, 1981 two of two specimens of the Lord Versilok 204 stressed to 1250 and one of two stressed to 1000 psi are still intact after 5.14×10^5 minutes. It appears that the endurance limit for the Versilok 204 is being approached at 1000 to 1250 psi.

Summary - The strength of adhesive bonds cannot be inferred from tests on bulk adhesive specimens. Such specimens do not measure the adhesion between an adhesive and an adherent nor do they place the adhesives in the stress states in which they normally work. The conventional tests used, i.e., the ASTM D897 butt tensile test and the ASTM D1002 single lap shear test are useful primarily for qualitatively comparing adhesives, not for obtaining basic strength data. It appears that the most suitable test for obtaining strength data consists of a tubular butt specimen

subjected to a combination of torque (producing shear) and axial loading. Such a test must be developed and refined.

A survey of available structural adhesives indicated that epoxies and modified acrylic adhesives are most suitable for applications on bridges. After preliminary small scale tests, Dexter Hysol epoxies and Lord Versilok modified acrylic adhesives were chosen for further evaluation.

Experimental study of adhesive bond properties requires a very sensitive transducer for measuring strain in the adhesive. It appears that a capacitance type [56] transducer is the most suitable. Placing electrical resistance strain gauges over bond lines is expensive and cannot capture the nonlinear portion of the stress-strain curve of an adhesive. A promising technique for measuring stress distributions is to place electrical resistance strain gauges on the adherend, adjacent to the bond-line.

Axial stress vs time to failure data showed that adhesive materials cannot be modeled simply as linear elastic materials. In any experiment the loading rate as well as the environmental conditions must be carefully controlled. Studies of joints subjected to pure flexure indicated that adhesives are capable of plastic deformation, although the thinness of the bond line makes such ductility difficult to observe.

CHAPTER VI

EXPERIENCE AND DESIGN PROCEDURES FOR ADHESIVELY BONDED JOINTS

Introduction - Chapters IV and V indicated that knowledge regarding adhesive and bond behavior, which in theory is required for engineering design of bonded joints, is quite incomplete. However, it is clear that adhesives have been used successfully in numerous, demanding applications. Therefore a sufficient knowledge base must exist in specific areas which allows satisfactory design of adhesive bonds. The intent of this chapter to to briefly examine adhesive bond design practice in the aerospace, automotive and civil/construction industries. Of course, adhesives are used in many other production/manufacturing areas but it is likely that the state-of-the-art in engineering design of bonds is most highly developed in the industries noted. Moreover, their design criteria for adhesive bonds is similar, or, in some areas, even more stringent than the design criteria which will be required for bridge applications.

Aerospace Use of Adhesives - Reinhart [68]gives a chronology of the use of adhesives in the aerospace industry; it represents approximately forty years of experience. Representative uses of metal to metal structural bonds on aircraft are as follows:

a) Bonding doubler plates or building up laminated parts
b) Bonding skin to stiffeners, ribs, stringers, etc.
c) Producing skin panel splices, with or without mechanical fasteners
d) Bonding a metal skin to a low density honeycomb core for production of "sandwich" panels.

The above uses indicate that adhesive bonds are used primarily in a shear mode. Therefore by far the largest engineering effort has been spent on

quantifying the shear behavior and strength of bonds. The state-of-the-art in analysis and design of bonded connections is probably embodied in the findings and recommendations of the PABST (Primary Adhesively Bonded Structure Technology) program, initiated in 1975 by the U.S. Air Force. The publications of Thrall [35] and Hart-Smith [60] present some of the results of that program. It must be remembered that their findings are applicable primarily to aluminum, titanium or composite adherends and may not be completely appropriate for mild steel.

Regarding bond aging, Thrall [35] states: "The corrosion/disbond problems long associated with bonded joints are understood and controllable". The primary method for controlling degradation appears to be the phosphoric acid anodizing process for adherends surface preparation. The process produces stable oxide layers, optimally 3000 Å thick [35]. Despite the progress noted by Thrall bond degradation remains an important problem. Reinhart [68] for one, cites the need for a "life prediction methodology for adhesive bonded components" and for "moisture resistant adhesives".

The PABST program has led to the development of an analytical procedure for the analysis and design of lap joints. The analysis of Hart-Smith [60] uses an elasto-plastic constitutive model for the adhesive and computes only shear stresses, normal or "peel" stresses are not considered. The effects of flaws and of decreased moduli in adhesive materials with absorbed water may be modeled in the analysis.

Overall, it appears that the design of adhesive joints in the aerospace field is still largely based on testing of prototype designs and on an extensive data base of in-service performance. This is a completely valid design methodology, as witnessed by the very successful use of adhesives

on aircraft. However, its adaptability to different applications, such as on bridges, is limited. An implication is that an engineering design approach based on constitutive material models, analysis, adhesive and adhesion strength theories and quantified degradation processes remains a long term objective.

Automotive Use of Adhesives - Structural adhesives are used extensively in the manufacture of automobiles and other vehicles. Beck and Yureck [93] note some of the past and current uses. It is important to note the similarities between automotive and bridge applications of adhesives. First, automotive bonding is often between mild steel adherends as on bridges. Second, preparation of automotive adherend surfaces is less elaborate than that of the aerospace industry, much more like what is feasible for bridges. (Modified acrylic adhesives, which cure quickly and require less surface preparation are beginning to be used in vehicle assembly). Third, the automobile environment i.e., salt, oil, moisture and temperature extremes, is similar to that of bridges. In fact, one of the motivations for using adhesives on vehicles is often to reduce fatigue cracking problems around conventional mechanical or welded connections.

No references have been found which detail the bond design methodology for vehicles. It is assumed that, as in the aerospace field, it is based on prototype testing and a data base of in-service performance. However, unlike aerospace applications, such a data base may be very useful for developing bond designs for bridges.

Civil/Construction Applications - Use of epoxy-based adhesives in concrete construction is commonplace. Patching or injection compounds for concrete repair, adhesive coated rebars and epoxies for bonding precast units are

some of the applications. Use of adhesives with metallic adherends is much less widespread. Metallic bearing surfaces of teflon bearings have been bonded and steel has been bonded to concrete either for strengthening purposes or to provide a shear transfer mechanism to achieve composite behavior.

In the U.S. studies on uses of adhesives to achieve composite behavior were conducted in the early 60's at the University of Arizona, at Rensselaer Polytechnic Institute and by the California State Highway Department. One of the experiments conducted by Kriegh and Richard [72] at the University of Arizona was a fatigue test of a full scale composite beam in which the maximum cyclic shear stress in the (epoxy-based) adhesive was 270 psi. It is reported that the beam withstood 3.8×10^6 cycles without failure of the bondline. Durability was a concern, and some accelerated aging tests were performed on bonded, but unstressed surfaces. However only qualitative descriptions of the "aged" bondlines were given.

Irwin [23] and Macdonald [24] report on experimental studies performed in England on the flexural behavior of concrete beams with bonded external steel reinforcement. The studies focus on whether composite action is achieved and on the failure mechanisms. Both cite the need for further investigation of the fatigue, creep and durability properties of the bond. Macdonald also notes the surprising fact that at least 240 bridges had been plated in Japan by 1975 [24]. Performance data from such applications would be useful. Dussek [58] notes that two bridges reinforced in 1975 and 1977 are performing satisfactorily to this date. However Dussek [58] also cautions that additional studies must be performed before plating techniques are recommended for general use. McKee and Cook [94] have performed some tests on concrete/metal floors with an adhesive to promote composite action.

Askins [52] provides data on durability of adhesives used in U.S. Air Force shelters for metal skin to core bonds and for metal to metal lap type bonds. Aluminum adherends and epoxy adhesives were used. Durability tests were conducted on stressed joints in conditions of high temperature and relative humidity. Seven epoxy adhesives were evaluated. All specimens stressed at 60% of their initial strength failed before 1000 hrs. Only a fraction of the specimens stressed at 40%-of-initial-strength level survived over 1000 hrs.

Summary - It seems that designers of adhesive bonds both in the aerospace and automotive industries use design procedures based on prototype testing and in-service performance data. The automotive experience may be more directly useful for bridge applications since there are similar environmental conditions and adherends. Civil engineering applications have focused on concrete and the limited number of applications/studies of steel to concrete bonds point to the need for studies on cyclic loading, creep and durability.

CHAPTER VII

ADHESIVES FOR BRIDGES: CONCLUSIONS AND ISSUES FOR FURTHER STUDY

The objectives of the study were to determine if adhesive bonds, as substitutes for certain welded connections, can improve fatigue lives of primary members and to examine the feasibility of designing steel to steel adhesive bonds for bridges. The following tasks were performed to address the latter, rather broad, objective.

i) Statement of general performance criteria

ii) Identification of suitable, available materials

iii) Examination of the current engineering analysis and design of bonds

CONCLUSIONS

1) The full scale experiments reported in Chapter I have shown that adhesive bonds can, in fact, improve fatigue lives. Adhesives can have sufficient static and fatigue strength to perform the structural function of certain welds.

2) Evaluation of an adhesive must include consideration of the necessary surface preparation and curing as well as its durability in the bridge environment.

3) Epoxies, modified epoxies and modified acrylic adhesives are the most suitable adhesives for steel to steel bonding. Acid anodizing processes for surface preparation are recommended primarily for aluminum and titanium adherends; grit blasting and solvent wiping are recommended for steel adherends. Manufacturers provide only sparse data on the chemical

composition and mechanical properties of adhesives.

4) Adhesive bonds show creep, relaxation and creep rupture behavior for a broad range of applied stresses. These properties indicate that linear elastic constitutive models of adhesives may be appropriate only for small stress levels. The strength of an adhesive material in a bondline cannot be inferred from uniaxial tests of bulk specimens without a strength theory. The adhesion strength of a bond is generally larger than the cohesive strength of the adhesive but it is more susceptible to degradation with time. Understanding and controlling bond strength degradation with time is a requisite for feasibility of bonding.

5) The ASTM D897 butt tensile test and the ASTM D1002-72 single lap shear test do not provide fundamental strength data. They may be used for qualitatively comparing adhesives. A promising test for obtaining strength data consists of hollow cylindrical butt joints subjected to axial and torsion (shear) loads. A capacitance-type transducer is probably the most accurate method for obtaining strains in bondlines. Electrical resistance strain gauges adjacent to bondlines are promising for measuring primary stress distributions in a bondline. Endurance limits for cyclic loading and for creep rupture are critical strength measures.

6) Adhesive bond design methods in the aerospace (and probably the automotive) industries are based largely on prototype testing and a data base of in-service performance. Aerospace expertise cannot be directly transferred to bridge applications because different adherends, environmental conditions and durability criteria are used. An implication is that engineering design of bonds based on material constitutive equations and strength theories for cohesion and adhesion is a long term goal.

Overall, design of steel-to-steel bonds for bridges is feasible if a set of basic strength tests are performed on adhesive bonds and if the durability problem is understood and controlled.

ISSUES FOR FURTHER STUDY

As noted, bond design procedures based on exact stress analyses and strength theories are a long range goal. The following studies may provide a sufficient data base for the development of approximate, conservative design approaches.

Small Scale Experimental Studies

a) Measurement of the elastic modulus, plastic yield range and the viscosity of adhesives.

b) Strength tests using an apparatus which can apply axial load and torque (shear) simultaneously.

c) Strength tests under cyclic loadings.

d) Strength of bonds in pure flexure.

The above studies should be performed under design environmental conditions and carefully controlled loading rates.

Experimental Durability Studies

a) Small scale durability tests of stressed bonds in destructive environments to determine extent of degradation, effects of bond area, membrane coatings or other means for improving durability.

b) Field tests of adhesive bonds on actual bridges.

Theoretical Studies

a) Degradation processes

b) Cohesive and adhesion strength theories

c) Constitutive models

Of the above theoretical studies the first is by far the most important.

Design Procedure

Based on experimental strength results and on estimated, limited bond degradation, an approximate, conservative working stress or strength design method should be developed.

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APPENDIX

COMPANIES TO WHICH A REQUEST FOR INFORMATION ON STEEL-STEEL ADHESIVES WAS MAILED

1. Adhesive Engineering Co.
   1411 Industrial Road
   San Carlos, CA 94070

2. Delta Plastics Co.
   7449 Avenue 304
   Visalia, CA 93277

3. Protex Industries Inc.
   1331 West Evans Ave.
   Denver, Colo. 80223

4. Sika Chemical Corp.
   Box 297
   Lyndhurst, N.J. 07071

5. Warner Engineering Services
   2905 Allesandro St.
   Los Angeles, CA 90039

6. H.B. Fuller Co.
   2400 Kasota Ave.
   St. Paul, Minnesota 55108

7. Dexter Hysol (Michael Fleming)
   322 Houghton Ave.
   Olean, N.Y. 14760

8. Bostic East
   Middleston, MA 01949

9. Amicon Corp.
   Polymer Products Div, Dept "R"
   25 Hatwell Ave.
   Lexington, MA 02173
   (617) 861-9600

10. 3M Company, (Leigh Nelson
    ACS Division, Dept. TR
    3M Center
    223 6th NE
    St. Paul, Minnesota 55101
    (612) 733-1110)

11. Loctite Corp
    999 N. Mountain Road
    Newington, Conn. 06111

12. Emerson & Cuming, Inc.
    Canton, MA 02021

13. Devcon
    59 Endicott St.
    Danvers, MA 01923

14. Furane Plastics, Inc.
    Los Angeles, CA 90030

15. Cibon-Ren Plastics
    Lansing, Mich.
    (481) 393-1500

16. Conap, Inc.
    Olean, N.Y. 14760
    372-9650

17. CIBA-Geigy
    Ardsley, N.Y. 10502

18. Hughson Chem.
    Lord Corp
    Erie, Pa

19. Armstrong Prod.
    Warsaw, Indiana 46580
    (219) 267-3226

20. Abatron, Inc.
    141 Center Drive
    Gilberts, Ill 60136
    (312) 426-2200

21. Palmer Products
    Worcester, Pa 19450

22. Multiple Coatings Inc.
    Baroda, Mich.
    (616) 422-1122

23. B.F. Goodrich
    Akron, Ohio

24. Eastman Chemical Co.
    Kingsport, Tenn. 37662

25. Reichold Chemical, Inc.
    White Plains, N.Y. 10603

26. Borden Chemical Div.
    Columbus, Ohio 43215

27. Diamond Shamrock
    Cleveland, Ohio 44114

28. DuPont de Nemours,
    Wilmington, Del. 19898

29. General Mills,Chemicals
    Minneapolis, MN 55435

30. Thiokol Corp
    Trenton, N.J. 98650

31. Exxon Chemical
    Houston, Texas 77001

32. Goodyear Tire & Rubber Co.
    Akron, Ohio 44316

33. Polymer Research Corp.
    Brooklyn, N.Y. 11234

34. Epoxilite Corp.
    El Monte, CA

35. Cryslerweld Cement Prod.
    Crysler Corp.
    Trenton, Mich.

CASE WESTERN RESERVE UNIVERSITY • CLEVELAND, OHIO 44106

15 November 1979

Gentlemen:

We have been awarded a contract by the Ohio Department of Transportation to perform research on adhesively bonded structural connections. The primary motivation for the research is that conventional attachment of secondary members by welding to primary steel bridge girders leads to a substantial reduction in the allowable live load stress range in the primary member. The following specific research objectives have been established:

a) Identify steel to steel adhesives for use in a bridge environment.

b) Conduct mechanical and other tests to verify the performance of selected adhesives.

c) Conduct fatigue tests on large scale specimens to demonstrate the utility of adhesive bonding techniques for increasing the allowable stress range in primary members.

This letter is part of the effort to identify suitable adhesives and manufacturers of such adhesives. Therefore, we kindly request the following information.

Does your firm manufacture adhesives which may be suitable for steel to steel bonding of secondary attachments on highway bridges? If so, can product data be forwarded to us? Specifically we need:

1. Mechanical (tensile, shear impact, fatigue, etc.) and chemical properties of suitable adhesives.
2. Data on durability, specifically in a bridge environment.
3. Data on any actual experience from similar applications.
4. Information on how to obtain appropriate samples of adhesives.

Any additional information or further cooperation in the work is entirely welcome. Please call me if you have any questions.

Thank you for your cooperation.

Sincerely,

D. A. Gasparini
Assistant Professor of Civil Engineering

Case Institute of Technology
School of Engineering
Department of Civil Engineering
(216) 368-2950